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A Hands-on, Introductory Course for First-year Engineering Students in Microsystems and Nanomaterials

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We have recently developed a one-credit course designed for first-year students considering the new major in Microsystems and Nanomaterials Engineering. It is based on a successful "Engineering Projects" course offered through our General Engineering department, which has subsequently been made into a popular summer program for prospective students. The goal of this new course, which meets two laboratory hours per week, is to expose students to several of the important ideas and concepts in microsystems and nanotechnology, and to give them hands-on projects that will help them learn these multidisciplinary ideas. Further, the "ulterior motive" of this course is to inspire students to stay in engineering, and to give them a flavor of the interdisciplinary nature of this field. The course progresses through several modules, which were created by faculty experts in each field. These modules are designed so that a single faculty member can conduct the course, and covers topics in: laboratory safety and cleanroom protocols; MEMS devices and scaling, including using a tabletop scanning electron microscope and a MEMS probe; fabrication including lithography, vacuum systems and thin film deposition; nanoscience; nanoscale measurements including principles of atomic force microscopy; nanobiotechnology; and societal issues. In addition to describing the course and its modules, we will also report on the results of the course and its two iterations.

Introduction

Many universities have incorporated hands-on engineering experiences for first-year students as a means of improving retention and students' understanding of the different engineering disciplines, as well as helping students select their major within engineering. At the University of Wisconsin-Platteville, we have developed a required course in which students rotate through short, hands-on modules for each engineering discipline on our campus, as a means of gaining an active introduction to each discipline.[1] Over 500 students per year move through this course. Further, this course has been adapted into a popular summer "camp" that has expanded from a single offering to three.[2] Additionally, the Electrical Engineering (EE) program created a similar, one-credit required laboratory course for first year EE majors, which focuses exclusively on electrical engineering content. Approximately 140 students per year move through this course, which has had a significant impact on boosting retention within that major. To this end, the Microsystems and Nanotechnology (MSNT) program at UW-Platteville implemented a one-credit lab for freshmen MSNT majors in Spring 2012. Since this is a new degree program, the purpose of this course is as much retention as it is exposure and recruitment of students to enroll in either the major or minor in MSNT.

The instructional goal of this course is rather straightforward: to expose students to several aspects of both microsystems and nanotechnology; to engage students in hands-on activities in both sub-fields; to excite students with the possibilities for these fields. An overview of the Spring 2012 offering is presented below. Overall, the plan of the course was to start at the "micro" scale, with MEMS (microelectromechanical systems) and microsystems, and progress to the nanoscale and finally to the intersection of nanotechnology and biotechnology. We wanted students to experience fabrication of nanomaterials, and also to make measurements on these. Also, we sought to inject as many applications as possible. Finally, due to the "overview" nature of this course, we have for now precluded introducing the operation of time-consuming instrumentation such as an atomic force microscope, which would have taken away from the range of topics we could cover. A description of the modules and their sources will follow.

Table 1. Week-by-week overview of the Introduction to Microsystems and Nanotechnology lab course.

Week	Topic
1	Introduction, Micro/Nano concepts and applications
2	Micro/Nano fabrication; Safety & cleanroom protocols
3	MEMS I
4	MEMS II
5	MEMS III
6	Graphene I
7	Graphene II
8	Graphene III
9	NanoPhysics & Measurement I
10	NanoPhysics & Measurement II
11	Nanoscience I
12	Nanoscience II
13	BioNanoTech I
14	BioNanoTech II
15	Societal/Ethics

Overview of Modules

The course was conducted in two rooms; a large physics lecture/laboratory room with PCs, projector and whiteboards, and in the "Nano Lab," which has chemical hoods and a low-dust space for sensitive equipment. Seven students enrolled in the course, which was team-taught by four instructors in this initial offering. The course met for a single two-hour session per week, for the 15-week semester.

Week One: Introduction

The course began in the physics classroom with an overview of the semester, and quickly moved to a presentation of some applications of microsystems and nanotechnology. Students explored some aspects of scaling with components of a "NanoDays kit," distributed by the Nanoscale Informal Science Education network (NISE Net).[3] (NISE Net is "a national community of researchers and informal science educators dedicated to fostering public awareness, engagement, and understanding of nanoscale science, engineering, and technology." They have several kits, which consist of freely downloadable instructions and source/price lists for the supplies.[4]) This kit had been obtained and utilized in a previous year as a successful part of an outreach effort with our campus' "Engineering Expo." Students explored the relative effects of static and gravitational forces for differently sized plastic beads, and also the effect of hydrophobic/hydrophilic sand.

Students also explored products that already incorporate nanotechnology by using "Nano Product Bags," which have nano-enhanced consumer products along with description cards: students learn about the product and present to each other. The bags originally came from the Penn State University NACK Center;[5] at present the resource is downloadable with guides on where the user can purchase these products.[6] This module was followed up with an assignment that had students search the online Nanotechnology Consumer Products Inventory[7] and present another nanotechnology-enhanced product.

Week Two: Safety and Cleanroom Protocols

The second week had the students meeting in the Nano Lab. Though it is not yet a cleanroom, we treat the space as if it were, restricting access and requiring booties, lab coats, and hairnets. This gets students used to the idea that a clean laboratory space has specific protocols to be followed. Students learned about chemical labels, MSDS and safe chemical handling, and safe handling of compressed gas cylinders. They then embarked on a "scavenger hunt" that had them identify different hazards in the lab, as well as the location of safety equipment such as the eye wash station and the emergency shower.

Students also learned about the different cleanroom classifications (i.e. ISO 1 through 9), the general "construction" of a clean room and sources of dust, and how to minimize dust. This led up to the rules of our clean lab. Students also used a MET ONE HHPC-2 handheld airborne particle counter to measure the cleanliness of different areas within the lab, as well as to monitor the effects of "unclean" behaviors such as talking over experimental samples, rubbing one's hands. This provided a direct, "hands-on" way to observe cleanliness – which can be hard to convey since a clean room may not appear "special" to the naked eye.

Weeks Three, Four and Five: MEMS and Microsystems

After a brief classroom presentation on the principles of scanning electron microscopy (SEM) and MEMS, the class moved to the Nano Lab. Students split into two groups and rotated between two stations. At one, students operated a Hitachi TM-1000 Tabletop Microscope to take SEM images of insects and MEMS devices. The tabletop microscope has been superseded, but was purchased for $60,000. It has proven especially hardy as literally scores of first-year students have operated it. Concepts of sample charging and resolution could be explored – in addition to the basic enjoyment of the images!

At the other station, students activated MEMS devices using an E M Optomechanical OptoPro 622A, a MEMS probe station. This is a long-working range microscope, equipped with a vacuum chuck for samples and wire probes to deliver a voltage to the MEMS device. The MEMS devices came by way of Sandia National Laboratory, since we are a part of the Sandia MEMS University Alliance program.[8] Unfortunately, we paid the price for not operating in a low-dust environment: after a few seconds of viewing the motions of a micro-scale oscillator, the system jammed irrecoverably.

The next week, students again began in the physics classroom, for an overview of microfabrication, before moving to the Nano Lab. In the lab, students used a vacuum trainer[9] to learn about the basics of vacuum, gauges, pumps, pump speed, etc. Additionally, students used the unit to deposit a thin film of zinc via evaporative deposition of brass onto a glass slide cover slip.

The thin film deposition was combined with a simple introduction to lift-off lithography, which the authors have not found in any reference. For this experiment, prior to deposition students draw a simple shape on their slide using both a Sharpie® and a Vis-à-vis® (wet erase) marker. After the film is deposited, students find they can lift off the Vis-à-vis pattern (and not the Sharpie's) by adding water to the film. They also find that acetone will lift off the Sharpie pattern – but not the wet erase marker's. This is a vivid yet simple (and safe) introduction to the ideas of specificity for etching.

The third week was spent making a three-level microfluidic mixer using the children's craft toy, "Shrinky-Dinks.[10]" Students were able to mix differently-colored water samples and explore aspects of microfluidics such as capillary action – and the problem of trapped air bubbles.

Weeks Six, Seven and Eight: Graphene Transistor

In a module that students reported as the highlight of the course, one of our instructors adapted a procedure to build a nanotransistor from graphene[11] into an undergraduate laboratory.[12] In the first session, students were presented with a lecture on fundamental aspects of graphene including synthesis and applications, followed by a lab exercise in which students generated graphene flakes using the "Scotch tape" method – more formally known as the Nobel prize-winning technique of mechanical exfoliation.[13] They then deposited the flakes onto a small conductive p-type doped silicon wafer.

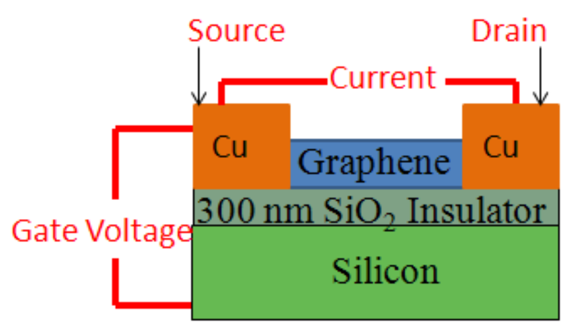

Figure 1. Schematic diagram of a graphene field-effect transistor.

In the second session, after a presentation on the fundamentals of electronics and transistors, they then used a microscope to lay a fine wire across the flake to act as a mask, and the instructor sputter-coated a film of copper over this, yielding the source and drain contacts. The third and final session consisted of students testing their graphene transistors with microprobes (the OptoPro MEMS probe, above) and verifying their operation by observing the voltage drop across the few-layer graphene at a known constant source-drain current as a function of the gate voltage.

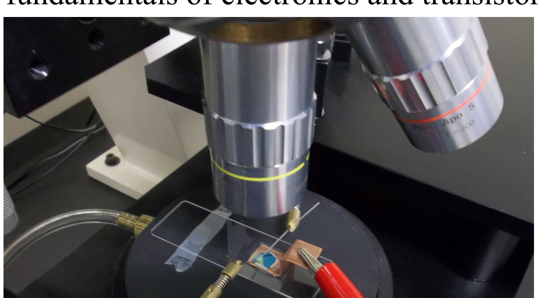
Figure 2. Testing the graphene transistor in the microprobe station.

Despite the challenging procedure and content, one freshman successfully constructed a working graphene transistor. (Common reasons for failure include a flake that is too thick or too small, and misalignment of the wire "mask.") It was heartening to find that the students appreciated the fact that this was a challenging protocol, and that all enjoyed the success of the one fortunate student.

Week Nine: Principles of Atomic Force Microscopy

In this week, students were presented the basics of scanning probe microscopy and carried out a "Move a Wall" experiment, which was developed by the University of Illinois and illustrates several aspects of the operation of an Atomic Force Microscope (AFM).[14] In this experiment, the small deflection that results from pushing on a brick wall is translated into sideways motion of a rod, which leads to the rotational motion of a mirror. By using the reflection of a laser off of the mirror onto a distant surface, students were able to determine that they had deflected the wall by mere micrometers. We then reconvened in the classroom to discuss results, and discussed more AFM operating modes, exploring the key idea of phase by way of an interactive demonstration. Since phase is a challenging concept to grasp, I have had success with a "tactile" interactive demonstration. In this demonstration, two-meter sticks simulate the AFM cantilever. A person holds them out in front of his/her body, one in each arm, and bobs up and down. The two sticks are seen (and felt) to oscillate in phase no matter how they are driven. However, if one stick experiences a force at its tip – in this case, the small gravitational force from an added C-clamp – then the stick is seen (and felt!) to oscillate out of phase with the bobbing motion.

Week Ten: Quantum Dots and Nanoparticles

This module focused on the optical properties of quantum dots and nanoparticles. Quantum dots are nanometer-size semiconducting particles, typically from two to ten nanometers in diameter. Because of their small size, they confine their excitons in all three dimensions and therefore have novel electronic and optical properties that can be controlled by their size and composition. In essence, they are "man-made atoms." Given that this involves quantum physics, the theoretical underpinnings can be somewhat abstract for students. We therefore tried to limit the presentation to the "big ideas." The session began with a presentation on the photoelectric effect and energy quantization, including the concept of atomic energy levels. It then proceeded into an overview of the physics and applications of these particles, emphasizing the differences between metallic nanoparticles and semiconductor quantum dots. Students explored these ideas with interactive simulations freely available at the PhET website, which has content relevant to these and many other concepts.[15]

After this, students moved to the lab were introduced to simple spectrometers (Ocean Optics' Red Tide) and used them to measure the emission wavelengths of quantum dots. They used their measurements – with a provided equation – to estimate the size of the particles.[16] They also observed the scattering and absorption of gold nanoparticles using a spectrophotometer setup (Ocean Optics). The main point of this part to show that (1) the scattered and absorbed wavelengths differed, and (2) this was distinct from the emissions of quantum dots. This day in particular was a little rushed, since a class day had been lost to a campus event; still, students were engaged and asked several questions.

Weeks Eleven and Twelve: Nanoparticle Synthesis and Surface Modification

After "playing" with nanoparticles the previous week, students were now given the opportunity to fabricate nanoparticles. A Chemistry professor (T. Wu) led these two weeks, which began with a presentation on nanoparticle fabrication techniques and then moved to the laboratory. Students conducted a standard synthesis of silver colloids by combining sodium borohydride and silver nitrate ($NaBH_4$ and $AgNO_3$). The colloid was analyzed by using light scattering: the reflection of a laser showed the presence of the particles, and 90° scattering of white light showed the predominant scattering to be in the yellow portion of the visible spectrum. The aggregation of the particles with added acid and base was also explored.

In a "twist" on this synthesis, the colloid suspension was finally used to create polyvinyl alcohol (PVA) stained "glass" (or in this case, plastic). After dissolving PVA solid into the heated colloid solution, the mixture was allowed to set, leaving yellow "glass.[17]" This mimics one of the earliest applications of nanotechnology – stained glass windows in medieval churches.

Finally, magnetic nanoparticles were created by coprecipitation, though time did not allow for much beyond verification of their magnetic properties.[18]

In the next week, students were introduced to the concept of self-assembly. In the lab, students learned another thin-film fabrication technique – electroless plating of silver. They then coated their films with self-assembled monolayers (SAMs) of alkyl thiols, which are long hydrocarbon chains with a sulfur atom at one end and a hydrophobic or hydrophilic group at the other. Through molecular interactions, these molecules form a single layer on the surface, with the exposed layer having the properties of the group at the end of the "chain.[19]" (See Figure **3**.) Students delighted in creating these strongly hydrophobic and hydrophilic surfaces, and the experiment led to much speculation on how they might apply this knowledge.

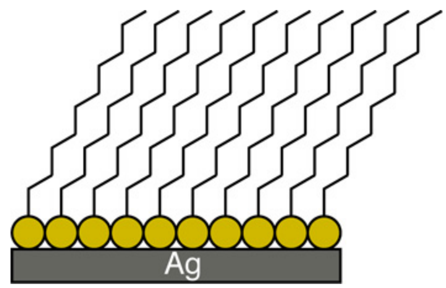

Figure 3. Schematic of self-assembled monolayer of alkyl thiol. Illustration from the UW MRSEC web site (Ref. 19).

Weeks Thirteen and Fourteen: NanoBioTechnology via ELISA

In the final laboratory module of the semester, we wished to expose students to aspects of nanobiotechnology. This was the field in which the instructors had the least experience and knowledge, so a biochemistry faculty member helped us to identify a kit that we could use to tag and identify proteins. We selected an ELISA kit for the detection of bovine TNF-alpha protein. ELISA is an acronym for enzyme-linked immunosorbent assay, an immunological assay technique that uses antibody binding and color changes to identify a substance. We used a kit from Bethyl Laboratories,[20] and adapted their procedure so that acceptable results could be obtained in under four hours of class time. As with other sessions, this one led off with a lecture on proteins and their structure, and on the nature and applications of antibodies.

The kit, in short, includes plastic wells that are pre-coated with a primary antibody for the TNF-alpha molecule (tumor necrosis factor). (TNF-alpha can induce cell death, and has been used to inhibit cancerous tumor formation; antibodies fit to target proteins via a "lock and key" mechanism and are highly specific.) Unknown samples, with different concentrations of TNF-alpha, were added to each well; the TNF was then bound to the well via the antibody. In subsequent steps, another "tagged" antibody was added to the wells: again, it was only bound in the presence of TNF-alpha. This ultimately led to a color change in the solution in the wells, the intensity of which is proportional to the concentration of TNF-alpha. The students made measurements using a plate reader – standard fare in a biochemistry laboratory – for quantification of their results.

While this served as a good introduction to a fundamental technique in protein manipulation and detection, the experiment itself was somewhat tedious for our students, with several "add solution and rinse" steps. However, this was the most "accessible" experiment we could find, and the ELISA technique is directly applied in a common product: the home pregnancy test.

Week Fifteen: "Nano-Ethics"

Finally, the course concluded with an interactive discussion on the ethical issues surrounding new technologies, specifically nanotechnologies. To this end, the class played a Democs "card game." Democs is an acronym for a deliberative meeting of citizens.[21] Developed in the United Kingdom,[22] these are a means for non-experts "to work out, share, and express their views on public policy issues." The "game" is made up of sets of cards ("Issues," "Information," and "Story"), and is not played to win, but sets up a semi-structured group discussion of complex technical issues through the medium of the cards. It is designed so that the general public can take part in discussions of the future directions of technology, with less reliance on expert facilitation. At the end of the discussion, participants vote on what "acceptable" uses of technology may be.

For our course, we used Democs materials on nanobiotechnology, developed by Edinethics Ltd. Their free report includes the content needed to create the set of cards.[23] The scenarios involve potential future applications of nanotechnology to medicine, as well as environmental effects and even "human enhancements." These cards led to a good discussion with positive student feedback. Having this exercise at the *end* of the semester, after the students had worked with each other and the professors for several months, undoubtedly helped the discussion proceed more smoothly: the participants felt comfortable with each other and all students contributed to the discussion.

Reflection by Students and Faculty

The anonymous student evaluations at the end of the semester show that the course was successful in its goal of inspiring them and encouraging them to learn more. Some sample student comments include (note that MSNT = "microsystems and nanotechnology"):

- "…lots of hands on activities, providing a broad base for the beginning of nanotech knowledge."

- “I only wish there was more time to explore further into each application/module.”
- “The course was very inspiring, … and I received a very good understanding of what I would be doing in the MSNT field.”
- “The lab work was my favorite part of the course and I learned the most from it.”
- “Loved the class. I thought it was a really good idea to bring in multiple professors… [this class] helped me decide if I really wanted to go into the nano-tech field.”
- “This course will make students want to take more MSNT classes because of all the creative labs that are done.”

A couple students identified the content as being challenging without background knowledge that they know they’d be gaining in future courses in chemistry or physics, but went on to comment that they were able to navigate the material in spite of this. For future offerings, we do plan to adjust the initial presentation of the topics accordingly – but the activities themselves will remain largely unchanged. In this sense, the course is a setup for “spiral teaching” in our major: it provides an initial, first-look at various topics that are later re-introduced at a more sophisticated level later in the students’ academic careers.

The faculty also felt that the course accomplished what it set out to do, though it was a lot of work for a course of its type: one credit of “exposure.” This was in part due to our desire to have as many engaging experiences as possible – but this was only practical because we had at least two interested faculty in the room at all times. This student-to-faculty ratio of 3.5:1 is not sustainable: for the long-term viability of the course, we need to be able to have the course run by a single instructor, or perhaps a single instructor with a few “guest” instructors for particular modules.

Future Directions

To make it easier for a single instructor to conduct the course, we are looking to hire an upperclassman student assistant, who would help the instructor with setup and work with the students in the lab. It is hoped that this will help build an identity with the new major, allowing first-year students to interact with a successful upperclassman.

In Spring 2013, we plan to include more MEMS content, which is not a strength of any of the instructors. Fortunately, since the 2012 offering, two of us have attended a workshop sponsored by the Southwest Center for Microsystems Education (SCME).[24] The NSF-sponsored SCME has a wealth of educational materials that are largely targeted at technology education, but also are readily adapted into a course such as ours.[25] Their materials are freely downloadable, and registered users (also free) have access to instructor guides and editable documents. Further, they sell classroom kits. We plan to implement elements of several of these, including (1) a MEMS pressure sensor fabrication activity; (2) a modeling of the MEMS pressure sensor itself, including a Wheatstone bridge; (3) a DVD on MEMS fabrication, with supporting materials;[26] (4) a “rainbow wafer,” which allows students to estimate silicon oxide thickness based on color, as well as to estimate etching rates. Our exact use of these modules is being determined as of this writing, as they will be used in three courses in the overall curriculum.

Additionally, we are moving the popular graphene transistor experiment out of this course and into a different, sophomore-level course, which has physics and chemistry prerequisites. This is because the nanoscale transistor has a rich array of behavior that can be explored – but would not be fruitful for the first year students. Additionally, for this module, the faculty felt that the students' lack of background knowledge genuinely hampered their understanding of what they were doing.

Since computation and simulation are an important part of micro- and nanotechnology, we feel that it is also important to add an activity of this type to this course. The cleanest "fit" with the rest of the course will be to explore the design of quantum dots. An excellent resource for such activities is the site NanoHUB.org, created by the Network for Computational Nanotechnology (NCN), an NSF-sponsored consortium of eight universities and laboratories. NanoHUB.org has a growing collection of simulation programs for nanoscale phenomena, plus online presentations, courses, learning modules, and more. The quantum dot lab allows users to select particle dimensions, shapes, and materials, and to view the resulting wavefunctions, energy states, and absorption spectra.[27] We plan to have the students use this tool to "design" a quantum dot for a particular transition energy; this will expose them to some of the tools that exist, as well as to the idea of "designing" a "man-made atom."

Other features under consideration include a tour of the labs and facilities associated with the major, and perhaps including other easy fabrications such as electrospinning of nanowires,[28] or spin casting thin polymer films (with measurements using our new Dektak XT profilometer).[29] Finally, in order to make the course even more engaging and to incorporate creative input from the students, we are strongly considering giving over the last three weeks of the course to student-defined projects. For instance, students may wish to explore the effect of changing the spin speed or material concentration on film thickness; or they may wish to improve the "ink-pen lift off" process or to investigate making hydrophobic/-philic patterns or the effect of temperature on quantum dot emissions. In general, these would be "obvious" extensions of experiments the students have already done. Students would present their results to the class in lieu of a final examination.

Conclusion

We are offering a "hands-on" survey course of microsystems and nanomaterials for first-year students. We are utilizing resources from NACK, NISE Net, SCME, Nano-CEMMS Center, nanoHUB, the UW MRSEC, as well as homegrown procedures. Initially team-taught, we are attempting to pare the course down to be manageable for a single instructor, and are moving to incorporate more MEMS and computational content.

Acknowledgment

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Appendix – Estimated equipment/supply costs

Week 1: Nanoproducts
- <$100 for nano products as described at Nano4Me.org. Reusable.
- NISE Net kits are $25 or less apiece. Reusable.

Week 2: Safety & Cleanroom protocols
- $3,000 for particle counter

Week 3-5: MEMS and Microsystems
- Tabletop SEM: $60,000
- MEMS probe station: $60,000
- Sandia's MEMS University Alliance: $5,000 license fee
- Vacuum trainer kit: $3,700
- Consumables (markers, acetone, glass slides, Shrinky-Dinks): <$25

Week 6-8: Graphene Transistor
- Graphite (HOPG): $110 to $260, depending on sample size. Consumable.
- Fine 0.001" wire, ~$100. Consumable.
- Copper film: could use vacuum trainer, with tungsten wire, <$50; or used sputterer $2,500
- Silicon wafer: <$75. Consumable.
- Microscope; power supplies; hot plate; Kapton tape

Week 9: Principles of AFM
- "Shop" lasers; CD pieces; tape, t-pins: <$50.

Week 10: Quantum dots and nanoparticles
- "Quantum particle in a box" (Cenco's quantum dots): $150
- USB Spectrometer (Ocean Optics): $1,400
- Gold nanoparticles (or precursor chemicals): $100. Consumable.

Weeks 11 and 12: Nanoparticle synthesis and surface modification
- Chemicals: silver nanoparticles (or precursor chemicals); silver nitrate; PVA; alkanethiol: <$350. Consumable.
- Various consumable "standard" chemicals (ethanol, ammonia, KOH).

Weeks 13 and 14:
- Bovine TNF-alpha kit (Bethyl Labs): $425. Consumable/perishable.
- Used microplate reader: $2,500
- Standard pipettors, tips, etc.

Week 15: NanoEthics
- No cost.

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