JOM, Vol. 64, No. 10, 2012
DOI: 10.1007/s11837-012-0450-x

Undergraduate Education in Nanotechnology and Nanoscience

NITIN CHOPRA[1,2] and RAMANA G. REDDY[1,3]

1.—Department of Metallurgical and Materials Engineering, Center for Materials for Information Technology (MINT), The University of Alabama, Box 870202, 301 Seventh Avenue, Tuscaloosa, AL 35401, USA. 2.—e-mail: nchopra@eng.ua.edu. 3.—e-mail: rreddy@eng.ua.edu

As a result of the expanding market of nanoscale devices and composites, it is becoming critical to train undergraduate students in this area and to make them aware of methodologies for handling and processing nanomaterials. The interdisciplinary nature of this field allows for the development of a common learning platform for several majors, including metallurgy, materials science and engineering, electrical and chemical engineering, chemistry, and physics. The global workforce needed to support this area is estimated to be 2 million by 2015.[1] Many large-scale initiatives exist via the National Science Foundation (NSF) Nanoscale Science and Engineering Centers (NSECs).[2–5] Several universities are offering educational activities, including certificate programs, minors, as well as bachelors', masters', and doctoral level degrees in nanotechnology.[6–13] Other major nanotechnology education initiatives include nanoHUB by Purdue University,[14] the Nanofabrication Manufacturing Technology at Pennsylvania State University,[15,16] Stanford University, and the College of Nanoscale Science & Engineering at the University at Albany, State University of New York. The latter two programs have been successful in commercializing their technology.[17] In such educational initiatives, resources are allocated for graduate and undergraduate research projects, curriculum development, and outreach to K-12 teachers and students. Some programs also target technician training.[18–21]

Nanotechnology concepts are not easily understood by the public,[22] making it difficult for scientists and engineers to impart information to the public, especially about the risks associated with this technology.[23] The same is true in the case of undergraduates who may not have sufficient knowledge of the area as a result of limited exposure; this is understandable considering the properties of matter, taught in traditional courses, break down in this size regime. Students are fascinated by the subject but often struggle with individual topics, especially with concepts like size and scale.[24] Students' grasp of nanotechnology can be enhanced by providing them with more opportunities to work with nonvisible phenomena promoting complex analytical and critical thinking. This approach is taken up by most educational programs, although implementation differs widely. One way to include a broad range of disciplines is to create an undergraduate course composed of discussions about societal impact,[25] including works of science fiction as a way to stimulate discussion.[26,27] Some researchers have developed educational activities to supplement existing courses, especially in the first 2 years.[28–31] Going beyond just adding modules, educators have created laboratory courses where freshmen synthesize ferrofluids, quantum dots, and carbon nanotubes (CNTs)[32,33] and upper level students construct and test scanning tunneling microscopes (STMs).[34] Yet another approach is to weave nanotechnology concepts into courses throughout the 4 years.[35–37] Many interdisciplinary courses have been introduced: One example organizes the course into reading, lectures, and activity components[38]; one course is oriented toward biological applications[39]; another integrates sustainability topics[40] or specialized computer architectures[41]; and other topics.[42,43]

Nanotechnology and nanoscience learning through lecture-based courses becomes more difficult when one considers the duration of a typical semester (~45 lectures for a 3-credit-hour course) in an academic setting, where students have to finish the major prerequisites that consume a large amount of time. The basic question that needs to be answered is how to educate undergraduate students in nanotechnology by using conventional fundamental concepts for a specific major. The answer to this question surely lies in our ability to derive a novel guiding track for undergraduate students that allows for early start of training in the area of nanotechnology and nanoscience, through freshman year to senior year. This approach could also allow for providing senior students an avenue to select their design projects in the area of nanotechnology.

A critical component of nanotechnology training for undergraduate students should focus on lecture-based courses and experimental laboratories that can provide students with hands-on learning and exposure to nanotechnology tools and methods. This also includes analysis of acquired data from experiments and understanding the role of dimensionality that results in unique properties of the nanomaterials. Such laboratories should aim at walking students through the whole nanotechnology lifecycle. This will allow students to gain hands-on training that encompasses the nanotechnology life cycle (Fig. 1): Materials selection, fabrication, biological interaction, devices, characterization, computational methods, and safety principles. Oral toxicity, safe handling, and storage of nanomaterials must be taught to students as safe handling, disposal, and storage of nanomaterials will not only be a necessary skill set, but also of great importance to society as the environmental and biological effects of nanomaterials are largely unknown and inconclusive.[44–46] This could be attributed to the large surface-to-volume ratio of nanomaterials, increasing their chemical reactivity compared with their bulk counterparts. By using this approach, students should be able to perform substantial design of a nanotechnology system in a subsequent senior design course.

An important aspect of training of undergraduate students in the area of nanotechnology is to initiate the training process from the freshman year. For example, a multidisciplinary lecture course at the freshman level may introduce students to phenomena and processes at nanoscale and build on basic principles of engineering, chemistry, physics, and mathematics. Such a lecture course could be coupled with a specific laboratory, for example, chemical synthesis of gold nanoparticles of different sizes and shapes. It is possible to observe different colors for nanoparticles, as a function of their sizes and shapes, by virtue of size-dependent light–matter interactions. A change in pH of a stabilized gold nanoparticle solution could lead to sudden change in the solution color as the nanoparticles aggregate or lose stability in solution, which further explains size-dependent optics. The instructor can directly relate to the photonic applications of such nanoparticles. The applications aspect of nanomaterials could be associated with societal impacts and the important part nanotechnology plays in our daily lives. Similarly, higher level laboratories could be designed for sophomore, junior, and senior level. A good example of a senior-level laboratory could be the photolithography method to develop metallic patterns or nanoscale lines on a silicon substrate and further testing the current–voltage relationships of the substrate and relating it to conventional concepts and Ohm's law. Such a laboratory will allow senior students to learn about semiconductor fabrication processes and enable them to visualize processes performed in the microelectronic industry. More such laboratory examples could be easily derived, such as plasma processing of nanopowders, electrocatalysts for fuel cell applications, carbon nanotubes for gas and chemical sensing, graphene, nanoscale heterostructures for photocatalysis, and nanofluidics.[47–60] These kinds of laboratories can be easily merged with a senior-level course focused on nano/microfabrication fundamentals, electronic materials, or manufacturing techniques and processes. The success of nanotechnology training through courses and curricula in the way described above may motivate the students to opt for summer research in this area, leading to a strong research experience for them and strengthening our ability to build a strong future nanotechnology workforce.

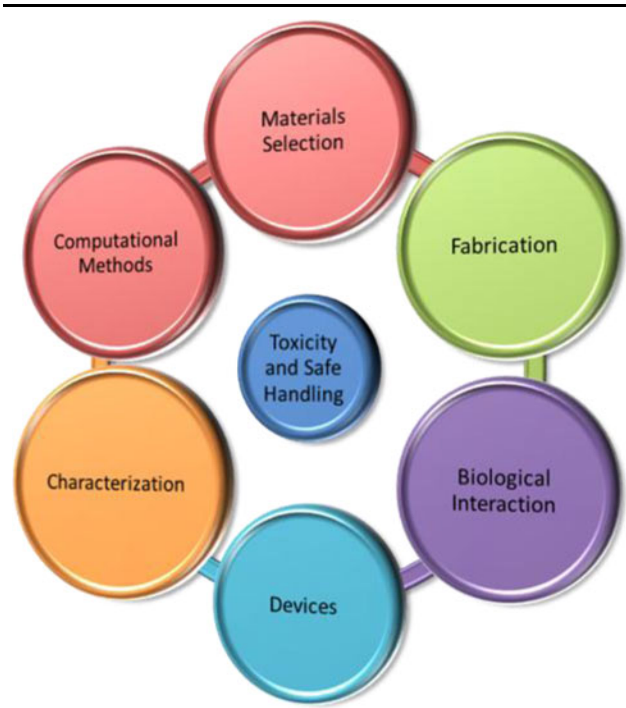

Fig. 1. A possible nanotechnology life cycle, which is initiated with materials selection. Toxicity and safe handling of nanomaterials is vital at any stage of this life cycle, and each stage could be related to any other stage.

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