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NANOTECHNOLOGY EDUCATION AND TRAINING

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ABSTRACT

Nanotechnology is regarded worldwide now as the technology of the 21st century and hence there is an imperative need to educate the future generation scientists and engineers about this emerging field. This article summarizes a two-unit course on the introduction to nanotechnology taught by the author at Santa Clara University and the nanotechnology internship programs at NASA Ames Research Center for high school, undergraduate and graduate students.

1. INTRODUCTION

Nanotechnology deals with creation of USEFUL/FUNCTIONAL materials, devices, systems, etc. through the control of matter at the nanometer length scale, say 1-100 nm at least in one principal direction. The terms 'useful and functional' are deliberately added here to the definition by the U.S. National Nanotechnology Initiative (NNI)[1] and emphasized to distinguish from the science fiction scenarios popularized by novels and press articles. The above statement regarding the length scale is only a necessary but not a sufficient condition. If the length scale is the only thing that matters, then essentially what is going on currently in silicon integrated circuit (IC) industry would be nanotechnology as they embark on sub-100 nm feature scale CMOS devices; in such a case we would be talking about education and training in ULSI (ultralarge scale integration) or post-ULSI, whatever that may be, instead of nano-technology education and training. These two areas are not at all synonymous. A sufficient condition would be that nanotechnology deals with taking advantage of novel phenomena and properties that arise because of the nano length scale. Indeed, physical, chemical, electrical, mechanical, magnetic, optical, and many other properties change in many instances as nanoscale is approached.

If a wide range of properties change due to the nano scale, then it is easy to understand the impact on a range of economic sectors: electronics, computing, data storage, communication, materials, manufacturing, health, medicine, energy, environment, transportation, national security, space exploration and beyond. In that sense, nanotechnology is an enabling technology as opposed to any single technology. In the last two hundred years, there have been a few other enablers such as textiles, railroads, automobiles and computers[2].

Nanotechnology as a unified field has started receiving much attention after the unveiling of the NNI in early 2000. This initiative resulted in substantial funding for basic and applied research in nanoscience and technology in the U.S. through various government agencies led by the National Science Foundation (NSF). The NSF has also established, through competition, science and engineering research centers in various nano themes at universities across the U.S. Nanotechnology fabrication laboratories (Nano fabs) and infrastructure networks have also been established. Since the beginning, much of the U.S. efforts have been matched by Japan and European union countries and to a lesser extent by Korea, Taiwan, China, Singapore, and Switzerland. In making such investments, all these countries have portrayed nanotechnology as the technology of the 21st century. The university-based research has started to generate valuable intellectual property in the U.S., which is the basis for new startup ventures. There is a reasonable venture capital activity in the field in the U.S. and appears to be growing. In addition, established small, medium, and large companies have been actively engaged in nanotechnology research and development.

The vigorous activities in the field mentioned above and the potential for the future point the need to educate the future work force about this emerging field. Indeed, the NSF has begun to make it mandatory to have a complementary educational component in all large center-size nanotechnology establishments. This has started to stimulate new courses and research experience for undergraduates in nanotechnology at some major research universities. Most universities have neither at this writing. Certainly, no U.S. university has a dedicated undergraduate BS degree in nanoscale science and technology as it is done at a few Australian and UK universities.[3] This is understandable from a U.S. perspective and traditional societal expectations since the existence of established industries and economies is a must for employing the newly-minted graduates which determines the fields of study a university offers; this is far from the case now, but likely to happen within a decade. In the meantime, it is important to offer elective courses and internship or training programs for highly qualified undergraduate students, and internships for even high school students. These are the subjects of this article. The author is not an academic but a scientist and Director of the Center for Nanotechnology at a national laboratory. This article describes a nanotechnology course the author has been teaching at a local university and a well-established nanotechnology internship program at his laboratory. It is hoped that these examples will serve as one possible model for those who plan to establish such programs in their institutions.

2. NANOTECHNOLOGY COURSE

Background

The author has offered for three years in a row a course on 'Introduction to Nanotechnology' at Santa Clara University (SCU). SCU is a private university in Northern California's Silicon Valley with about 8000 students. It is primarily a teaching institution with a small fraction of full time graduate students. The Electrical Engineering (EE) department is one of the handful of departments offering a Ph.D. program. A significant fraction of the student population is drawn from the Silicon Valley companies and consists of mature aged students. This course is primarily from the EE department though once co-numbered with mechanical engineering. In general, the course has drawn a few students from other majors such as chemistry, physics, ME, ChE, but mostly EE. Such a mix may be occasionally challenging to the instructor both in terms of searching for common terminologies/language and emphasis on application areas in the syllabus. Some students have been from SCU's Master's Program in Engineering Management. They have engineering undergraduate degrees and in this class they are treated like any other engineering students. That is, engineering management students are not given any non-science or non-technical assignments and no topics related to nanotechnology business management are covered. The author's core belief is that managers ought to have a strong basic and technical background in what they are managing.

The course is open to undergraduates, primarily seniors since they would have all their basic course requirements completed, and to first year graduate students. There is a substantial overlap in the skill set of these two groups and hence, there is no need to distinguish the two in terms of project assignments or expectations. The course is a 2 unit course and SCU operates on the quarter system. The quarter system lasts about eleven weeks.

Course Syllabus

The syllabus for the 2-unit course and the approximate time for covering each topic are given below. The total number of contact hours for instruction is about 18 hours over ten weeks (with once a week meeting) with the eleventh week assigned to exams or project presentations.

1. Introduction (45 min.)
2. Nano vs. bulk properties (2 hr.15 min.)
3. Tools (1 hr.)
   - Electron microscopy
   - AFM
   - STM
   - Other techniques
4. Processing techniques (2 hr.)
   - Top down techniques
   - Bottom up techniques
5. Nanomaterials
   - Carbon nanotubes (2 hr.30 min.)
   - Inorganic nanowires (1 hr.)
   - Other materials (1 hr.30 min.)
6. Nanoelectronics (3 hr.)
   - Novel devices
   - Novel architectures
7. Other application areas (2 hr.)
   - Sensors
   - Field emission
   - Thermoelectric devices
8. Nano-bio (2 hr.)

The details on what is covered under each section are given in the next section. The time allotted to each topic above is approximate and balanced between fundamentals and applications. Extending this to a 3-unit semester course should be straightforward, mostly by extending the coverage on most topics and/or by adding additional topics such as nanophotonics.

What is EE-specific about this syllabus is section 6 and somewhat of an electronics / computing / data storage / communication emphasis when discussing applications. The syllabus can be used without modification for physics majors. This course can be modified for mechanical engineers by replacing section 6 on nanoelectronics with composites and generally shifting application emphasis to such areas as fuel cells, nanoelectromechanical systems, nanofluidics, heat transfer, thermoelectrics, and system integration. For material science major, there should be a balance between the two sets of applications above. The last section on nano-bio is considered vital for all majors. In principle, with nanoscale science and technology emerging as interdisciplinary field, there should not be any emphasis based on the traditional divisions of science and engineering departments, at least when discussing fundamentals, properties, tools and processes; it is likely that the discussion on applications areas would tend to run along traditional divisions.

Course Coverage

There is no prescribed text book for this course since there is none available in the market at present. The students are given a copy of the author's viewgraphs ahead of time. In addition, research articles and book chapters on relevant topics are assigned for reading.

The introductory class covers the definition of nanotechnology, in essence, what the field is about (and also what it is not) and its history. The history dates back to Chinese pottery makers and Venetian glass blowers. In that sense, it is important to emphasize that many existing technologies do already depend on nanoscale materials and processes. Photography and catalysis are two additional examples of 'old' nanotechnologies[1]. All of the above were developed centuries or decades ago, as the case may be, when no capabilities existed to probe matter at the nanometer scale. As pointed out by the NNI architects, most of the current technologies that have successful examples of using nanomaterials and been around a long time like the above examples, were discovered by serendipity[1]. At that time, no one understood the role of the nanoscale; with the understanding comes improvements and rational design of advanced materials and systems. The historical perspective discussion ends with Feynman's visionary lecture[4] and the advent of scanning probe microscopes. In the introductory lecture, the potential of nanotechnology in various economic sectors and its role as an enabling technology are pointed out.

The discussion on nanoscale properties, indicating what is special about the nanoscale and how properties are different from those of their bulk counterparts, lays the foundation for the entire course. Nanoscience deals with the in-between-world, the one between atoms/ molecules studied in chemistry and solids of infinite arrays of bound atoms dealt by the condensed matter physics[5]. In materials, the extent of delocalization of valence electrons as well as structure changes with size; these two changes lead to different physical and chemical properties depending on size. The discussion dwells on melting point, specific heat, conductivity, bandgap, color, surface reactivity, optical properties, magnetic properties etc. as a function of size[5]. Change in surface to volume ratio or ratio of atoms on the surface vs. bulk atoms is illustrated with particle size and correlated to chemical reactivity, catalysis, etc. For example, single-walled carbon nanotubes (SWNT) were shown recently[6] to have a surface area of ~1600 m^2/g. The fact that the surface area of 4 gms of nanotubes is about the same as an American football field illustrates the impact of using such nanomaterials as catalyst support and gas adsorption. In this section, various definitions are also made to introduce clusters, colloids, nanoparticles, nanocrystals, nanocapsules, nanoporous materials, nanofibers, nanowires, and quantum dots. A quick background on adsorption including various adsoption isotherms is provided reminding what was learnt in earlier physical chemistry courses. This is done in conjunction with the discussion of the large surface area of nanomaterials to emphasize applications in catalysis, sorbents, etc.

Section 3 deals with tools mostly for imaging techniques. A very brief introduction to optical, scanning and transmission electron microscopes is provided followed by a detailed discussion of atomic force and scanning tunneling microscopes. Specialized characterization techniques used in material characterization such as Raman spectroscopy, FTIR, UV-VIS-NIR spectroscopy and other analytical techniques are not covered here but can be in a 3-unit semester program.

Section 4 deals with both top-down (briefly) and bottom-up processing techniques. Top-down apparatus are currently used widely in the growth/preparation of nanomaterials as well as in the fabrication of nanodevices. Though this group of students have a general background in microelectronics fabrication, a quick refresher is provided on sputtering, CVD, plasma processing, etc.; otherwise, the major focus of this section is on techniques such as self assembly, sol-gel processing, 3-D printing etc.

A detailed discussion on various nanomaterials is the next focus with carbon nanotubes (CNTs) being the first candidate. CNTs have generated an amazing level of excitement due to their unique electrical and extraordinary mechanical properties[7]. Their relation to graphite and fullerenes, structure, and helicity are presented first followed by a discussion of properties as we know now from both theory and measurements. Videos[8] depicting what happens when a nanotube is bent, stretched, compressed or twisted are used to illustrate the mechanical properties. On CNT preparation, laser ablation and arc synthesis are covered briefly followed by a more detailed account of CVD and plasma CVD based approaches. An important aspect in CNT growth is the role of the transition metal catalyst and the coverage includes catalyst preparation techniques (solution based vs. physical approaches such as sputtering, evaporation), growth mechanism (tip growth vs. base growth, catalyst poisoning), effect of catalyst particle diameter and layer thickness on CNT growth, and relation to earlier generation materials such as carbon fibers and filaments.

Application focus is an important aspect of this section and it begins with the use of CNTs in scanning probes[7]. Applications in imaging metallic, dielectric, and semiconducting thin films in metrology, imaging of biological materials in dry form as well as in their natural aqueous environment, and profilometry in semiconductor processing are covered. Distinctions are made between conventional probes and CNT probes in terms of resolution and robustness. The next application relates to nanoelectronics in computing and data storage[7]. Here, early configurations of CNT based diodes, transistors and simple logic elements are introduced with a strong emphasis on their limitations. Other applications[7] include field emission and sensors with a lighter coverage on composites and structural applications.

The inorganic nanowire discussion begins with the difference in characteristics between the one-dimensional wires and two-dimensional thin films. Results from Raman spectroscopy and other techniques comparing bulk samples, thin films, and nanowires of zinc oxide are used to illustrate the differences. Various methods to prepare nanowires are mentioned with an emphasis on vapor-liquid-solid approach as it appears to be the most widely reported in the literature.[9] Applications related to devices including vertical transistors[10], lasers, and sensors are covered. It is important to recognize that a high temperature oxide such as tin oxide in its 2-d incarnation has long been advocated for chemical sensors in the form of the so-called chemical field effect transistor (CHEMFET) and therefore a connection needs to be made for the use of 1-d configuration in terms of sensitivity, integration density, fabrication and other advantages, if any.

The nanoelectronics section starts with the anticipated progress in Si CMOS technology and roadblocks according to the Semiconductor Industry Association (SIA) Roadmap[11] and a reading assignment of an article[12] on this topic along with emerging technologies that appeared in IEEE Circuits and Devices Magazine. The expectation from emerging alternatives is emphasized in terms of cost of manufacturing, high current drive, reliability, life time, number of transistors per chip, and heat dissipation issues. Vertical top gate[10] and vertical surround gate transistors using silicon nanowires can meet some of the SIA metrics using a known material like silicon in the next several years. Beyond that, alternative materials such as CNTs and organic molecules in electronics are introduced followed by alternative (to CMOS) architectures such as fault-tolerant, neural, and evolvable architectures as well as alternative state variables such as electron spin.

Other key areas to benefit from nanotechnology include sensors: physical, chemical, and bio sensors. Variables include temperature, charge, mass, conductivity and a host of other properties with the nature of the signals ranging from electrical, electrochemical to optical. Though fabrication and operating principle of single sensors is discussed, the emphasis is shifted to system integration. Field emission is another important application covered in addition to thermoelectric refrigeration, catalysis, and gas adsorption/storage.

The final section on nano-bio starts with the basics of DNA, DNA chips, gel electrophoresis, and integrated devices for DNA analysis. After this introduction, the coverage includes DNA conductivity and DNA computing. The pioneering work by Adleman[13] is discussed in detail by focusing on the Hamiltonian path problem. Other subjects in this section include transport through ion channels, construction of ion channels, gene sequencing using synthetic nanopores and biosensors.

Project Assignment

In this course, no homework assignments are made and there are no midterm or final exams either. Each student is assigned one project and the course grade is based solely on the project report and the oral presentation. Project assignments are made at the first meeting of the year and therefore the students have all the ten weeks to work on it. Throughout the term, they can receive help from the instructor on an as-needed basis. The presentations, about 15 minutes long including time for a few questions, are scheduled during the exam week at the end of the term. The project report is expected to be about 10-15 pages including figures, tables and references. The following is a sample of projects assigned:

- Quantum computing
- Fault tolerant architecture
- Evolvable hardware
- Neural architecture for computers
- Spin based transistors
- Molecular electronics
- Nanotechnology in photonics
- Quantum dots
- Plastic electronics
- Dip pen lithography
- Soft lithography
- Biomedical sensors
- Peptide nanotubes
- Dendrimers
- Self-assembly processes
- Nanofluidics
- Biocompatible nanomaterials for transplant
- Nanoelectrodes for sensing and biomedical applications
- Nanoelectromechanical systems
- Nanotechnology in drug delivery
- Biosensors for Homeland Security

The project assignment does not involve any experimental work; instead the students are expected to explore this as a research proposal. The focus is not on simple literature search and regurgitation but forming an informed opinion on the current issues and challenges in the field and possible solution paths. Taking carbon nanotube probes in AFM as an example[14], the expectation from a project assignment may be as follows:

- How is imaging of various materials currently done? What are the limitations?
- What are the critical dimension metrology requirements in the SIA roadmap?
- Where does AFM based metrology fit in the current scheme of things in imaging and metrology?
- How does an AFM work?
- How is the conventional AFM probe fabricated? What is its performance level?
- What is the user feedback on conventional probes in terms of resolution, longevity, etc.? How does performance match up with expectation?
- What are the perceived advantages of using nanotubes for probes?
- How is a CNT probe fabricated?
- Data on its performance for imaging various materials?
- What are the issues associated with resolution, robustness, interpretation of results, general usage? Possible solutions?
- How would you approach large scale fabrication of these CNT probes?
- What aspect can be tackled on a Master's thesis?

Stating the level of expectation as above is important to allow the students to judge the work load, research methods, etc. The students are warned against relying on Google extensively or exclusively. This generally is not a problem as returns on most search engines are more of news report documents on the subject of the project and not peer-reviewed articles in archival journals.

3. NANOTECHNOLOGY TRAINING

While courses are meant to introduce the subject to a large number of students, internship opportunities to a select group of highly skilled students help prepare them towards a research career. We have started an internship program in 1998 for high school and undergraduate students. In each category, about 10 students are brought in during the summer for 10 weeks. The Undergraduate Student Program (USRP) and the High School Student Research Program (HSRP) are administered by the NASA Ames Education Office (*http://education.arc.nasa.*

gov). The selection is done on a competitive basis from student applicants across the U.S. These are paid internships and campus housing to students is available.

Each student is assigned a project and mentor from a group that consists of about 60 scientists working on various aspects of nanotechnology. The NASA Ames Center for Nanotechnology (NACNT) is an interdisciplinary group of physicists, chemists, molecular biologists, electrical engineers, mechanical engineers, chemical engineers, material scientists and computer scientists. The materials research consists of carbon nanotubes, inorganic nanowires, organic molecules for logic and memory, and protein based structures. The application focus consists of electronics, computing, data storage, optoelectronics, chemical and biosensors, nanolasers, gas adsorption and storage, carbon nanotube interconnects, thermal management, nanotechnology in gene chips and gene sequencing, and biomedical devices. This portfolio gives a broad range of topics to the students for selection depending on their interest and field of study.

Most of the student projects are experimental in nature though on rare occasions, computational projects are assigned if the student interest and aptitude warrant it. It is recognized that high school students aged 16-18 and even junior level undergraduates will not have the necessary background or the coursework for the research topics mentioned above. They are encouraged to read relevant research papers throughout their stay but get started in the lab as soon as they arrive after a day of safety training. Most of their early experience involves sample preparation, operation of a CVD or plasma reactor to grow nanotubes or nanowires, scanning electron microscopy, electrical characterization and similar operations and procedures.

Students are presented at the start with a goal for their project so that they can work towards a target instead of merely functioning as a helper. This also encourages independent efforts with occasional help from the mentor on an as-needed basis, safety related supervision, and help with explaining the results. An example of this is a high school student project involving a parametric study of growth variables on multi-walled carbon nanotube growth characteristics. The parameters in a PECVD process include inductive power, substrate bias, pressure, and feed stock flow rate/composition. The expected output is the ability to grow vertical, individual free-standing nanotubes. The effort starts with preparing a thin layer of iron catalyst sputtered on a silicon substrate, preparing the reactor for growth (evacuating to high vacuum, heating to desired temperature), actual growth for a pre-determined time, and sample inspection using SEM. Visual inspection of chamber walls every few days for amorphous carbon buildup is critical to avoid contamination. This is followed by a chamber cleaning procedure using an oxygen plasma. The entire scope of this project was well within the reach of a bright high school student. Adding other characterization results from the mentor and colleagues, the effort resulted in a journal article[15].

The students attend a weekly group meeting where they have an opportunity to learn more by osmosis. During the last week, the interns make oral presentations at the NACNT group meeting as well as to their peers at a NASA-wide meeting of the summer interns. In addition, they have to prepare a report outlining their work. These requirements provide them the training in public speaking, report writing, literature search, assessing their work against published results, and finding the context of their work in a broad field.

The HSRP and USRP have been extremely successful. A majority of students have co-authored publications with their mentors. A number of students have returned to Ames for one or two more years because they enjoy and value their experience. Invariably, every high school student from the HSRP has gone onto a leading university as a science or engineering major and every undergraduate student from the USRP has gone onto graduate school.

In addition to this focused summer effort, undergraduate students from local universities participate in research activities during the school year; the program during the school year is more flexible to accommodate class schedules. Other elements are very similar to the summer program.

In all of the above programs, there is a focused effort to recruit students from the Historically Black Colleges and Universities (HBCUs). In addition to the NASA-sponsored programs, the National Association for Equal Opportunity (NAFEO) sponsors[16] undergraduate and graduate students as well as faculty from HBCUs to participate in nanotechnology research programs at NASA Ames.

Other educational activities at NACNT include graduate student research programs[17] which involves hosting students from collaborating universities and summer faculty visit program administered by the American Association for Advancement of Science[17]; these programs provide USRP and HSRP students opportunities to interact with graduate students and faculty and learn about higher education programs. As a part of these educational activites, a webcast[18] on Introduction to Nanotechnology for high school and community college students has been developed and development of interactive education tools in nanotechnology for K-12 is currently in progress.

4. SUMMARY

Nanotechnology, as an enabling technology, is expected to have an impact on all sectors of the economy in the 21st century, starting in a decade or so. There is an urgent need to educate the future work force about this emerging field. Major research universities with their faculty actively engaged in nanotechnology research have the necessary expertise to assemble and offer courses in this field as evidenced by the trend in the last couple of years. These courses typically are at the graduate level and occasionally as an elective course at the senior undergraduate level. It is important to extend such opportunities to smaller, non-research colleges and universities, which may be done in a number of ways: professional scientists/engineers teaching at these institutions as adjunct instructors, possible cross-listing of courses from major universities through strategic partnership, and distant learning approach through video or web. Major universities with established nano centers can also offer the same course during the summer for high school and community college teachers. In this article, a 2-unit course on introduction to nanotechnology has been described in detail as a possible model. Nanotechnology internship programs to select highly-skilled high school and undergraduate students have also been discussed. These programs are designed to attract young students to stay interested in science and engineering and to pursue a career in research.

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