AC 2012-3735: A MODULAR APPROACH FOR TEACHING A FIRST UNDERGRADUATE COURSE IN NANOELECTRONICS

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A Modular Approach for Teaching a First Undergraduate Course in NanoElectronics

Abstract

The paper describes the development and teaching of a first undergraduate course in nanoelectronics. The uniqueness of the course lies in the following facts: It is modular in structure. Computational nanotechnology has been made an integral part of the course. It provides hands-on experience with real samples and equipment. High-Performance Computing Cluster (HPCC) has been used for modeling and simulation. The course has been developed for a university that does not have many state-of-the-art facilities available at larger research universities, and at the same time caters to a student population with great diversity in background preparation. The course was offered at the junior/senior level to electrical engineering majors. The main objectives of the course were to teach the characterization and fabrication of nanomaterials, simulation of nanomaterials and devices, operation and design of devices, and the design and fabrication of integrated circuits, at the nanoscale. The course was divided into four modules and was developed by four faculty members using an iterative procedure. The four faculty members had expertise in the areas of nanoscale fabrication and characterization, computational nanotechnology, nanoscale devices, and nanoscale integrated circuits. The four modules in the course were introduction to nanoscale fabrication and characterization, basic computational nanotechnology, introduction to nanoscale devices, and introduction to nanoscale integrated circuits. The course was taught during Summer Semester 1 of 2011, by the four faculty members who developed the course. A detailed course schedule, which specified topics which were to be covered each day, was given to the students. The modules were taught in the following sequence: Basic computational nanotechnology, Nanoscale fabrication and characterization, Nanoscale devices, and Nanoscale integrated circuits. Students were assigned grades on the basis of in-class assignments and projects. Students evaluated instruction at the end of each module by anonymously filling in a questionnaire. At the end of the course, students provided their feedback about the course. The course was well-received by the students.

Introduction

For nearly the last twenty years, nanotechnology has been advertised as the future of the electronic industry. Towards this end, many universities across the country, and around the globe, have been actively developing undergraduate nanotechnology education and research programs. For example some of these institutions are: University of Houston (Nanoengineering Minor Option), Georgia Tech (Nanotechnology Certificate Program for Undergraduate students), Carnegie Mellon University (Interdisciplinary Undergraduate Program in Nanotechnology), Louisiana Tech University (Bachelor of Science degree program in Nanosystems Engineering), Rensselaer Polytechnic Institute (ENGR-1600 Materials Science for Engineers), and University of Waterloo (Canada) (Nanotechnology Engineering BASc program). Clarkson University (Potsdam, NY) is developing an undergraduate course suitable for a relatively smaller research intensive university.

While all these programs will lead to better background preparation and content of courses related to nanoelectronics, there are several challenges which lie ahead. One of them is the need to increase minority students' exposure and participation in this exciting field. Concurrently, to reach the widest diversity and number of students, there is a critical need to develop undergraduate nanotechnology education programs and nanoelectronics courses in universities that are not research intensive, and therefore lack the infrastructure available to larger institutions.

The paper describes the development and teaching of a first undergraduate course in nanoelectronics at Texas A&M University-Kingsville which is one such institution. It is the first of a sequence of two courses. The second course will be a research project oriented course in which the students will build upon the foundation laid in the first course and apply the concepts and techniques learned to solve real-world problems in nanoelectronics.
The uniqueness of the course lies in the following facts: it is modular in structure; computational nanotechnology has been made an integral part of the course; it provides hands-on experience with real samples and equipment; High Performance Computing Cluster (HPCC) has been used for modeling and simulation. Modeling and simulation are indispensable in understanding the physical processes in nanoscale devices and their design and development.

Educational Environment

As a Hispanic Serving Institution (HSI), with a nearly 63% Hispanic student population, Texas A&M University-Kingsville (TAMUK) is uniquely positioned to increase the number of underrepresented students obtaining engineering degrees with an understanding of the field of nanotechnology. TAMUK has been one of the top ten universities nationally for a decade that provides education and training for future Hispanic engineers. The American Society of Engineering Education (ASEE) ranks TAMUK ninth in the nation in graduating Hispanic engineers[1]. At the same time, while TAMUK has a very active sponsored research program in several science and engineering disciplines, it lacks some of the critical research infrastructure in nanoengineering that is available to large research universities. The student population at TAMUK also has an enormously wide diversity in terms of socio-economic background, and preparedness for pursuing a degree in engineering. Many students are among the first in their family to pursue a college degree, and several have families to support while attending classes. However, as the PI and co-PIs have observed over their long years as faculty members at the Department of Electrical Engineering and Computer Science, TAMUK, what many of these students may initially lack or the challenges they may continually face, they make up with their dedication and desire to learn and work at the forefront of technology.

It is within this context that the nanoelectronics course was developed and taught. It constitutes a first step in a proposed program which aims at developing a long-term nanotechnology program at TAMUK, with a foundation being first laid at the Department of Electrical Engineering and Computer Science. Once developed, the program is expected to not only benefit the student and faculty community at TAMUK, but also a sizable number of universities across the nation that find themselves in a similar situation. The proposed program will be developed under two constraints:

1. It will aim at a diverse student population, and at a university that lacks the infrastructure of large research universities.
2. It will aim to develop a feedback mechanism involving suitable metrics and assessment plan to improve course content and teaching methodology.

A careful analysis of the available resources indicated that the short term objectives of the program can be achieved in the amount of time available if it is focused on students whose major is Electrical Engineering.

Course Development

The course development was guided by the following principles:

1. Electrical Engineering students will be introduced to wide-ranging aspects of nanoelectronics through a course targeting senior/junior level students.
2. Students will be provided knowledge and skills which will enable them to participate in nanotechnology research and development work.
3. The course will be modular in structure, thereby allowing flexibility in pedagogy and easy adoption by other courses/departments/universities.
4. Suitable metrics will be developed which will enable the measurement of students' learning and effectiveness of teaching in nanoengineering related courses.

The course was divided into four modules in the areas of nanoscale fabrication and characterization, computational nanotechnology, nanoscale devices, and nanoscale integrated circuits. The content of each module was developed by a faculty member having expertise in the area of the module. Keeping in view the guiding principles, the time constraint, and the background of students, faculty members suggested tentative topics to be included in their respective modules. The topics were also selected in such a way that topics in one module provided foundation for the topics in the succeeding module. The proposed topics were then analyzed and discussed by the four faculty members. In the light of these analyses and discussions, modifications were made to the topics. After several such iterations, the topics to be included in individual modules were finalized.

Course Modules

The course consisted of the following four modules: Introduction to Nanoscale Fabrication and Characterization, Basic Computational Nanotechnology[2], Introduction to Nanoscale Devices, and Introduction to Nanoscale Circuits. To understand the rationale behind the selection of the topics for individual modules, the course objectives and learning outcomes are summarized. The main objectives of this course were to teach the characterization as well as fabrication of materials at the nanoscale, the simulation of materials and devices at the nanoscale, the principles of the design of devices at the nanoscale, and the principles of the design of logic systems at the nanoscale. After the successful completion of this course, the student will be able to understand the characteristics and behavior of materials and devices at the nanoscale, to design simple logic systems at the nanoscale, and to do a research project in the field of Nanoelectronics.

A detailed description of these individual modules follows.
Introduction to Nanoscale Fabrication and Characterization Module consisted of the following

topics:

1.0 Fabrication (3 hrs)

1.1 Deposition Techniques:

1.1.1 vacuum technology, chemical vapor deposition (plasma-enhanced and thermal), sol-gel (chemical solution deposition), evaporation processes, plasma and ion beam processing, other techniques: sputtering, pulsed laser deposition, combustion/flame/aerosol CVD

1.2 Cleanroom and photolithography techniques

1.2.1 photoresist, masks, mask-aligner, etching, etc.

2.0 Structures and Devices (1 hr)

2.1 Carbon Nanotubes

2.2 Photovoltaics, Field Emitters

2.3 Transistors, Nanogenerators, Nanoantenna

2.4 Optical waveguides

3.0 Characterization (2 hrs)

3.1 Scanning Electron Microscopy – theory, application

3.2 Transmission Electron Microscopy – theory, application

In this module, a JEOL Model JSM-6701F SEM-EDX *Field Emission-Scanning Electron Microscope (FE-SEM)* and a Keithley 4200-SCS Semiconductor Characterization System were used. Prior to the start of the module, the instructor fabricated various nano-devices such as carbon nanotubes field effect transistors and solar cells. These devices and structures were used for demonstration. Students were able to observe these devices under the microscope, and characterize their electronic and optoelectronic responses using the characterization system.

Basic Computational Nanotechnology Module consisted of the following topics:

4 hrs. * Formulation of Carrier Transport Problem
* Hamiltonian Mechanics
* Essentials of Quantum Mechanics, Schrodinger's Equation

4hrs. * Atomic Structure (Periodic Table)
* Crystal Lattices, Scattering
* Energy Bands in Solids, Tunneling

3 hrs. * Semi-Classical Carrier Transport
(Boltzmann Transport Equation and Poisson Equation based algorithms)

The formulation of Carrier Transport Problem was done in terms of the motion of charge carriers under various forces. Due to the dual nature of these carriers at the nanoscale, particles and waves, it was shown that Hamiltonian Mechanics, as opposed to Newtonian Mechanics, was more suitable for studying the motion of these carriers. Three basic postulates of quantum mechanics, quantization of certain physical properties, wave-particle duality, and uncertainty principle, were discussed. Schrodinger's Wave Equation was developed. Its use in the solution of some basic problems was discussed. The Potential Well problem was used to discuss Tunneling. After describing the Bohr's Model, Atomic Structure of Elements and Periodic Table of Elements were discussed. Physical characteristics of crystalline solids and associated concepts were discussed. Carrier scattering due to ionized impurities and phonons was discussed. Energy Bands in solids were discussed. Boltzmann Transport Equation was derived and its use in the solution of Carrier Transport problem was indicated.

It is, thus, obvious that this module was used to build the formalism of computational nanotechnology from first principles. Students not only learnt the mathematical equations which are used in the modeling and simulation of nanoelectronic devices but also the physics and materials science underlying them.

Nanoscale Device Module consisted of the following topics:
2 hrs *Review of basic device physics, diode, BJT, and MOSFET operations
2 hrs *Nanotubes and nanowires – physical structure and electronic and optoelectronic properties of carbon nanotubes and silicon nanowires
2 hrs *Semiconductor heterostructures, Heterostructure field effect transistors, HBTs, transferred electron effects and NDR, Quantum wells, quantum dots and wires, Quantum dot cellular automata, Resonant tunneling and devices, Quantum Computing, molecular and biological computing
2 hrs *Device modeling of field-effect transistors incorporating nanotubes and nanowires – classical and semiclassical approach
3 hrs *Device simulations on HPCC

Introduction to Nano-Scale Circuits Module consisted of the following topics:
1. Current VLSI technology (3 hours)
    - Complementary metal-oxide-semiconductor circuits
    - Limitations of CMOS technology at nanoscale
    - CMOS scaling Issues
2. Nanoscale Alternatives (1 hour)
    - Tri-Gate transistors
    - Multi-Channel Tri-Gate transistors
    - Gate-All-Around transistors
3. Electrical Properties of modern nanoelectronic FETs (1 hour)
    - Carbon nanotube
    - Silicon nanowire
4. Fabrication process issues at nanoscale (2 hours)
    - E-beam and Advanced nano-lithography
    - Self assembly and Spun-coating
5. Computer aided design and simulation tools (1 hour)
    - Introduction to layout and simulation tools
    - Tool limitations
    - Nanomanipulation

Teaching of the Course and Grading

The course was taught during Summer Semester 1 of 2011, by the four faculty members who developed the course. It was taught Monday through Thursday for 2 hours each day.
Ten Junior students with major in Electrical Engineering enrolled in the course. The instructors had personal interaction with most of these students starting in Spring 2011 during which the enrollment campaign was conducted.

A detailed course schedule, which specified topics which were to be covered each day, was given to the students. The modules were taught in the following sequence: Basic computational nanotechnology, nanoscale fabrication and characterization, nanoscale devices, and nanoscale integrated circuits.

Since the emphasis of the course was on learning the basic concepts and applying them to understand the operation of various devices, students were assigned grades on the basis of in-class assignments and projects.

Instruction Evaluation

Instruction evaluation was done by means of surveys. In addition to an End-of-Course survey, surveys were conducted at the end of each module. Since the instructors had developed good rapport with the students, even before the course started, they considered themselves to be participants in the development of the course and provided valuable feedback and suggestions for the improvement. The course was well-received by the students. They agreed with the statement that the course was useful for their studies and career preparation. They indicated that, as a result of taking the course, they felt better prepared to work in the nanotechnology field. In the light of the experience gained by faculty members as well as feedback from the students, the course is being revised and will be offered again in Spring 2012 semester. A more formal and quantitative instruction evaluation plan is under development and will be implemented during this next offering of the course.

Another important indicator of the effectiveness of the course will be the performance of students in the companion research project course in which two groups of students are currently enrolled. Each group has been assigned a real-world nanoelectronics problem.

Conclusion

A new approach to teaching a first course in nanoelectronics has been presented. Recognizing that the modeling and simulation plays a very significant role in understanding the operation of electronic devices at the nanoscale, basic computational nanotechnology has been made an integral component of the course. Students have been introduced to computational nanotechnology from the ground up, that is starting from the basic postulates and concepts of quantum mechanics and solid state physics. Students actually carried out the simulations using High Performance Computing Clusters. The modular structure of the course provides enough flexibility to instructors to adapt the course to the educational environment in which the course is being taught. The feasibility of this approach has been demonstrated by teaching the course to a small group of students at TAMUK. Further refinement of the course structure, the course content, and the teaching technique are planned for the future.

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References

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