120th ASEE Annual Conference & Exposition
FRANKLY, WE DO GIVE A D*MN
June 23-26, 2013

Paper ID #6641

A NanoElectronics Concept Inventory: a tool to assess learning of fundamental concepts

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Abstract

Recognizing that the understanding of fundamental concepts related to the operation of nanoelectronic devices is essential for their modeling, design, and development, we have developed a senior/junior level course to teach these fundamental concepts to students in the electrical engineering major. It was followed by a design projects course in which students designed and implemented a nanoelectronic device. We developed the Nanoelectronics Concept Inventory to assess student learning of fundamental concepts in the first course. The assessment can be used to improve and enhance pedagogical techniques employed. The assessment can be supplemented by the observation of student performance during the design project course. A literature search indicated that ours is the first attempt at the development of a nanoelectronics concept inventory. The NCI was developed by a process which has been widely used for the development of concept inventories for various subjects. In NCI, the concepts were grouped into three categories: computational nanotechnology, nanoelectronics devices, and nanodevice fabrication. Each multiple-choice question related to a single concept with one correct answer and three incorrect answers (distractors). The NCI has been administered and the data have been analyzed using the observed performance of students on the design projects. The results so far have been very encouraging.

Introduction

It is widely recognized that understanding of fundamental concepts related to the operation of nanoelectronic devices is essential for their modeling, design, and development. These fundamental concepts are from the areas of Hamiltonian Mechanics, Quantum Mechanics, Solid State Physics, and Semiconductor Materials. It is very challenging to teach these fundamental concepts to undergraduate students in such a way that they not only have a good understanding of the concepts but also are able to apply them to solve problems associated with the design and development of nanoelectronic devices.

We have developed a senior/junior level course to teach these fundamental concepts to students in the electrical engineering major. The course is unique in the following ways: 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. It was followed by a design projects course in which students designed and implemented a nanoelectronic device. We developed the Nanoelectronics Concept Inventory (NCI) to assess student learning of fundamental concepts in the first course. The assessment can be used to improve and enhance pedagogical techniques employed. The assessment can be supplemented by the observation of student performance during the design project course. The paper describes the development, the contents, and the results obtained by the administration of NCI. A literature search indicated that ours is the first attempt at the development of a nanoelectronics concept inventory.

Related Work

A number of course inventories have been developed as tools for improving both learning and teaching of courses which are considered to be of fundamental importance in various disciplines. Among them is the Force Concept Inventory (FCI) which was designed "to address six conceptual dimensions within the field of force and related kinematics"[2]. In their paper, the authors reviewed the development of FCI, outlined its structure and reviewed findings from its implementation. Shallcross developed a concept inventory for assessing student learning in a basic material and energy balance subject[3]. His aim was to identify the misconceptions that the students may have when they start the subject. By comparing the pre- and post- test results an assessment could be made of the extent to which these misconceptions have been corrected. A Chemical Engineering Fundamentals Concept Inventory (CEFCI) was developed and implemented by Ngothai and Davis[4]. Their main objective was to have a quantitative means for predicting areas in which course development could be focused. Using statistical methods, they performed a rigorous analysis of test results. Bristow et al. proposed a Control Systems Concept Inventory (CSCI) for improving the teaching and learning in introductory control systems courses[5]. They used classical test theory and item response theory to analyze the aggregated test results for assessing internal consistency and measurement error, respectively. Padgett et al. attempted to extend the usefulness of the Signals and Systems Concept Inventory (SSCI) by applying it in a variety of situations other than that for which it was originally developed[6].

More relevant to NCI are concept inventories which have been developed for electric circuits and electronics. Vanderwalle has discussed a number of critical concepts for the Mathematics of Circuits and Systems which should be included in a concept inventory[7]. He has described the role of these concepts in the mathematics courses, which are taught first, and circuits and systems courses, which follow. Ogunfunmi and Rahman have described some key concepts related to Electric Circuits of which students should have good understanding[8]. They have given examples illustrating the fundamental concepts associated with basic circuit elements and their different configurations. In a follow-up paper, they have proposed a set of multiple choice questions for the Electric Circuits Concept Inventory (ECCI)[9]. These questions are related to fundamental circuit concepts, circuit laws and circuit analysis techniques. Scott et al. have described their work "to develop and verify a Threshold Concepts inspired inventory assessment tool in the field of electronics and simple circuit theory"[10]. They discussed the general structure of an electronics concept inventory, An Electronics Threshold- Concept Inventory and some example questions. They collected data with some Precursor Questions and discussed the results. A literature survey found no report of any recent developments related to electronics concept inventory.

Course Description

Courses on Introductory NanoElectronics are still being developed by a number of investigators and institutions. A consensus has yet to emerge regarding the fundamental concepts which must be taught in such a course. A standard NanoElectronics Concept Inventory has to wait until such a consensus is established. The NCI has been developed on the basis of basic concepts which we have proposed for a first course in NanoElectronics. To understand the rationale for the proposed concepts, it is necessary to understand the learning objectives and the structure of our proposed course[1].

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 consisted of the following four modules: **Introduction to Nanoscale Fabrication and Characterization, Basic Computational Nanotechnology, 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 brief description of these individual modules follows (detailed description can be found in reference 1).

Introduction to Nanoscale Fabrication and Characterization Module consisted of the following topics: Fabrication (Deposition Techniques, Cleanroom and photolithography techniques), Structures and Devices, and Characterization (Scanning Electron Microscopy, Transmission Electron Microscopy).

Basic Computational Nanotechnology Module consisted of the following topics: Formulation of Carrier Transport Problem, Hamiltonian Mechanics, Essentials of Quantum Mechanics, Schrodinger's Equation, Atomic Structure (Periodic Table), Crystal Lattices, Scattering, Energy Bands in Solids, Tunneling, and Semi-Classical Carrier Transport (Boltzmann Transport Equation and Poisson Equation based algorithms).

Nanoscale Device Module consisted of the following topics: Review of basic device physics, diode, BJT, and MOSFET operations, Nanotubes and nanowires – physical structure and electronic and optoelectronic properties of carbon nanotubes and silicon nanowires, 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, Device modeling of field-effect transistors incorporating nanotubes and nanowires – classical and semiclassical approach, and Device simulations on HPCC.

Introduction to Nano-Scale Circuits Module consisted of the following topics: Current VLSI technology (Complementary metal-oxide-semiconductor circuits, Limitations of CMOS technology at nanoscale, CMOS scaling Issues), Nanoscale Alternatives (Tri-Gate transistors, Multi-Channel Tri-Gate transistors, Gate-All-Around transistors), Electrical Properties of modern nanoelectronic FETs (Carbon nanotube, Silicon nanowire), Fabrication process issues at nanoscale, and Computer aided design and simulation tools.

NCI Development and Description

Depending on the context, availability of background material and the objectives, several investigators have adopted various processes for the development of their concept inventories. Bilici et al. used the following process for the development of their Astronomy Concept Inventory[11]: The inventory was developed based on the theory of test construction. The purpose of the inventory was identified and the concept domain was defined. To establish content validity, a table of specifications was specified to ensure representation of all the objectives of the curriculum. 12 questions were taken from eight different sources and 18 questions were developed by the researchers. After item analysis of test data, the final version of the inventory consisted of 25 items.

Herman et al. created a Digital Logic Concept Inventory by using concepts obtained from instructor feedback. Items were created by using distractors from misconceptions found during problem solving interviews with students.

Simoni et al. developed an Electronics Concept Inventory by first defining the scope of the subject material and listing the concepts within the scope[13]. In the next step, questions related to individual concepts were developed from problems using a number of heuristics.

Common among all of these processes are two major steps: specification of fundamental concepts and development of multiple choice questions related to these concepts. The NCI was developed by using this two-step process.

Researchers identified fundamental concepts in their individual modules. The compiled list of all the concepts was reviewed by all the researchers to make them consistent and to eliminate any redundancy which may be present. After a few iterations the following concepts were considered to be fundamental to the nanoelectronics course which was proposed and taught:
Computational NanoElectronics concepts: Conservative Force, Hamiltonian, Wave-particle Duality, Quantization of Energy, Uncertainty Principle, Schrodinger's Equation, Pauli's Exclusion Principle, Quantum Mechanical Tunneling, Four Quantum Numbers, Energy Bands, E-k Diagrams, Fermi energy, Fermi Function, Work Function, Drift, Diffusion, and Boltzmann Transport Equation.
NanoElectronics Devices concepts: Band Diagram, Band Bending, and p-n junction.
NanoElectronic Fabrication concepts: Deposition, Lithography, Etching, Implantation, MOSFET operation, Complementary Logic, Scaling, and Nanowire and Nanotube Fabrication.

After finalizing the concepts, researchers formulated the multiple choice questions. Researchers relied upon their experiences to select the distractors. These distractors will be further refined as more experience is gained with teaching of the course and supervision of design projects.

The NCI, which is included in its entirety in the appendix, consists of 24 questions. The first 13 questions are on computational nanoelectronics concepts, the next 4 questions (questions 14 thru 17) are on nanoelctronics devices concepts, and the final 7 questions (questions 18 thru 24) are on nanoelectronic fabrication concepts. Questions 1 thru 13 deal with concepts which are self-evident. Question 14 deals with the effect of doping on band diagrams, 15 with the effect of applied potential on band diagrams, 16 with the production of current, and 17 with the operation of Field Effect Transistor. Question 18 deals with layout and mask transfer, 19 with CMOS architecture, 20 with scaling obstacles, 21 with the effect of scaling, 22 with material etching, 23 with material properties, and 24 with the role of depositions in fabrication processes.

NCI Administration, Results, and Future Work

The NCI was administered to a small group of students after taking the Introduction to Nanoelectronics course. The results were consistent with the grades obtained on the basis of in-class assignments, projects and exams. The results were further validated by the performance of the students on the projects. Since before taking the course, students were not exposed to any of the subject matter taught in the course, it is reasonable to assume that their knowledge of nanoelectronics was entirely due to the instruction which they received.

As more data are collected by the administration of NCI, it will be possible to establish more rigorously its reliability and validity using classical test theory and item response theory[15, 16]. Additional studies, similar to that reported by Herman and Handzik[14] , can be carried out for improving pedagogy of nanoelectronics courses.

Conclusion

A NanoElectronics Concept Inventory (NCI) which can be used to improve the teaching and learning of nanoelectronics has been presented. A literature search indicated that ours is the first attempt at the development of a nanoelectronics concept inventory. The NCI was developed by a two-step process which has been widely used for the development of concept inventories for various subjects. In NCI, the concepts were grouped into three categories: computational nanotechnology, nanoelectronics devices, and nanodevice fabrication. Each multiple-choice question related to a single concept with one correct answer and three incorrect answers (distractors). The NCI has been administered and the scores have been analyzed using the observed performance of students on the design projects. The results so far have been very encouraging. Further work to improve the quality of distractors and to establish reliability and validity of NCI is planned.

Acknowledgements

This project was supported by the grant EEC-1042056 from the National Science Foundation Nanotechnology in Undergraduate Education (NUE) program.

Appendix – A Nanoelectronics Concepts Inventory

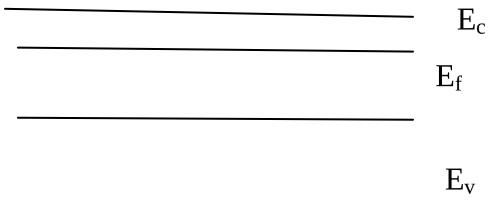
1. A conservative force is a force
    a. which results in conservation of momentum.
    b. which may be related to a scalar potential by a negative derivative.
    c. which is applied by persons having conservative views.
    d. which does not change when applied successively to different bodies.
2. The Hamiltonian for a conservative system with a velocity-independent potential energy is
    a. a constant of motion, if it is not explicitly time dependent.
    b. the total energy of the system.
    c. both a and b.
    d. neither a nor b.
3. The Wave-Particle duality refers to the phenomenon in which atomic particles while in motion
    a. appear to float around
    b. create waves
    c. behave sometimes as waves and sometimes as particles
    d. cause ripple effect
4. Quantization of energy refers to the observation that
    a. energy is radiated and absorbed in discrete "quanta" or "energy elements".
    b. small amounts of energy must be used for best results.
    c. restricted use of energy leads to conservation of energy.
    d. a fair distribution of energy requires its division into equal parts.
5. The Uncertainty principle states that
    a. nothing in this world is certain.
    b. the outcome of any experiment cannot be predicted.
    c. the simultaneous measurement of position and momentum is inherently inaccurate.
    d. ambiguity leads to uncertainty.
6. Schrodinger equation
    a. specifies how the quantum state of a physical system changes with time.
    b. is to quantum mechanics what Newton's second law is to classical mechanics.
    c. enables the determination of the wave function of a particle.
    d. all of the above, a, b, and c.
7. According to Pauli Exclusion Principle
    a. particles with high energy are excluded from any stable system.
    b. no two identical particles may occupy the same quantum state simultaneously.
    c. particles with low energy and those with high energy appear to interact in an exclusive manner.
    d. antisymmetry in wave functions of particles is the result of chemical bonds.
8. The term quantum tunneling refers to the phenomenon where a particle
    a. reaches the other side of a barrier that it classically could not surmount.
    b. displays wave-particle duality of matter.
    c. both a and b.
    d. neither a nor b.
9. Energy bands
    a. are ranges of allowed energies when electrons are brought into close proximity in forming a crystal.
    b. arise naturally when allowed energy states of electrons, moving in periodic potential

are considered.
  c. both a and b.
  d. neither a nor b.

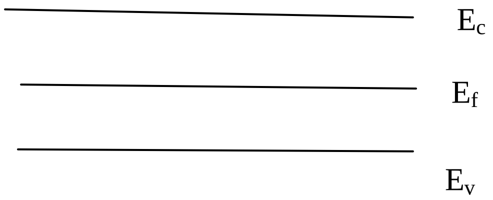
10. Fermi energy
    a. is the energy of highest occupied quantum state in a system of electrons at absolute zero.
    b. is also known as electrochemical potential
    c. both a and b.
    d. neither a nor b.
11. Drift is
    a. random movement of electrons
    b. the result of thermal agitation of charged-particles.
    c. charged-particle motion in response to an applied electric field.
    d. the result of elastic vibrations of crystal lattices.
12. Diffusion
    a. is a process in which particles migrate from regions of high particle concentration to low concentration.
    b. arises as a result of thermal agitation not due to interparticle interaction.
    c. both a and b.
    d. neither a nor b.
13. Boltzmann equation
    a. is an equation of time variation of a carrier distribution function.
    b. assumes that carriers behave as classical particles.
    c. both a and b.
    d. neither a nor b.
14. What is the correct band diagram for a p-type semiconductor:

a.

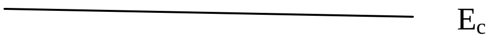
b.

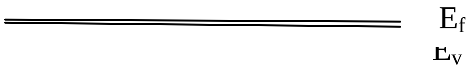


c.

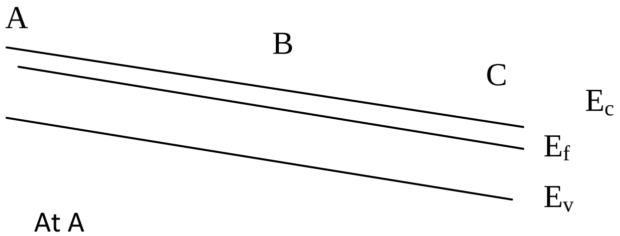


d.





15. In the band diagram below, at which point (A,B,C) will the holes have lowest potential energy?



- a. At A
- b. At B
- c. At C
- d. At A and B

16. What is the dominant current component across a forward biased junction?
   - a. Drift
   - b. Diffusion
   - c. Mainly drift with some diffusion
   - d. Mainly electrons with some holes
17. Applying a positive voltage at the gate of a field-effect transistor makes the semiconductor to become more:
   - a. P-type
   - b. N-type
   - c. Doped
   - d. Charge Neutral

18. The photolithography process is analogous to which of the following processes?
   - a. Writing on stone
   - b. Photographic process
   - c. Scanning process
   - d. Curing process
19. For an N input complementary logic circuit, how many transistors are required?
   - a. 2
   - b. 2N
   - c. N
   - d. N-1
20. Name two MOSFET limitations at nano-scale?
   - a. Gate oxide and interconnects cross talk
   - b. Hot electron and parasitics
   - c. Latch-up and leakage current
   - d. Field effects and channel resistance
21. The Moore's law is due to?
   - a. Price of silicon reduction over time
   - b. Larger wafers
   - c. Transistor size scaling

    d. Modern circuit architectures

22. Which of the following processes can create undercut edges?
    a. Wet Etching
    b. Dry Etching
    c. Annealing
    d. Plasma Etching
23. The process responsible for creating N-type and P-type regions is known as?
    a. Mixing
    b. Annealing
    c. Deposition
    d. Implantation
24. Which process can be used to transfer a material onto the wafer?
    a. Physical and Chemical vapor deposition
    b. Electrochemical deposition
    c. Atomic layer deposition
    d. All of the above

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