AC 2011-2008: FROM MICROELECTRONICS TO NANOELECTRONICS INTRODUCING NANOTECHNOLOGY TO VLSI CURRICULA

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From Microelectronics to Nanoelectronics – Introducing Nanotechnology to VLSI Curricula

Abstract

In the past decades, VLSI industries constantly shrank the size of transistors, so that more and more transistors can be built into the same chip area to make VLSI more and more powerful in its functions. As the typical feature size of CMOS VLSI is shrunk into deep submicron domain, nanotechnology is the next step in order to maintain Moore's law for several more decades. Nanotechnology not only further improves the resolution in traditional photolithography process, but also introduces many brand-new fabrication strategies, such as bottom-up molecular self-assembly. Nanotechnology is also enabling many novel devices and circuit architectures which are totally different from current microelectronics circuits, such as quantum computing, nanowire crossbar circuits, spin electronics, etc. Nanotechnology is bringing another technology revolution to traditional CMOS VLSI technology. In order to train students to meet the quickly-increasing industry demand for next-generation nanoelectronics engineers, we are making efforts to introduce nanotechnology into our VLSI curricula. We have developed a series of VLSI curricula which include CPE/EE 448D - Introduction to VLSI, EE 548 - Low Power VLSI Circuit Design, EE 458 - Analog VLSI Circuit Design, EE 549 - VLSI Testing, etc. Furthermore, we developed a series of micro and nanotechnology related courses, such as EE 451 - Nanotechnology, EE 448 - Microelectronic Fabrication, EE 446 – MEMS (Microelectromechanical Systems). We introduce nanotechnology into our VLSI curricula, and teach the students about various devices, fabrication processes, circuit architectures, design and simulation skills for future nanotechnology-based nanoelectronic circuits. Some examples are nanowire crossbar circuit architecture, carbon-nanotube based nanotransistor, single-electron transistor, spintronics, quantum computing, bioelectronic circuits, etc. Students show intense interest in these exciting topics. Some students also choose nanoelectronics as the topic for their master project/thesis, and perform successful research in the field. The program has attracted many graduate students into the field of nanoelectronics.

1. Introduction to Nanaoelectronics

In the past decades, VLSI technology has achieved tremendous progress. Based on VLSI technology, computers and information technology have greatly changed the life style of our modern human society. In the VLSI industry, there has been a constant drive to shrink the size of transistors [1]. In this way, more and more transistors can be integrated into the same chip area to make VLSI circuit more and more powerful. According to Moore's law [2], the amount of transistors in the same chip area is approximately doubled in every 12~18 months. Moore's law has been proved to govern the VLSI industry very well in the past decades. The transistor size has been shrunk into deep submicron or even nanometer domain. Nowadays a state-of-the-art Intel Xeon Microprocessor MP X7460 (6-core processing, 2.66GHz) based on 45nm technology contains 1.90 billion transistors [3]. This has enabled computers to be much faster and more powerful than before. As the transistor size continues to shrink, nowadays it is already approaching the bottom physical limit of traditional optical photolithography process. The minimum line width of modern microelectronic fabrication process is now comparable to the optical wavelength of the exposure light used in the photolithography. As a result, nowadays VLSI industry is facing a bottle neck to continue shrinking the size of transistors. In order to maintain Moore's law for another several decades, a brand new technology – nanotechnology, must be introduced into VLSI industry [4].

Nanotechnology is the science and engineering involved in the design, synthesis, characterization and application of materials and devices with the size in nanometer (10^{-9}m) scale. As a newly emerged exciting high-technology, it has attracted intensive interest among global researchers and induced heavy investments from governments, industry and research agencies around the world. Nanotechnology is a general-purpose technology which will have significant impact on almost all industries and all areas of society. It can offer better built, longer lasting, cleanser, safer and smarter products for home, communications, medicine, transportation, agriculture and many other applications. In nanotechnology, individual atoms and molecules are manipulated to integrate with each other to construct devices and circuits via bottom-up self-assembly process. This is totally different from the traditional top-down fabrication strategy. As a result, extremely high resolution comparable to the size of individual atoms and molecules (~ astrons) can be automatically achieved. Furthermore, it results in much less waste and extremely high energy efficiency during device fabrication. Utilizing bottom-up self-assembly for VLSI fabrication, minimum line width of several astrons can be easily obtained. As a result, this brings the hope to further continue Moore's law for another several decades.

As an interdisciplinary technology, nanotechnology requires knowledge and skills from many different fields, such as physics, chemistry, biology, electrical engineering, mechanical engineering, computer science, etc. Nanoelectronics is an interdisciplinary field between VLSI technology and nanotechnology. The relationship is shown in Figure 1. Nanotechnology is expected to bring a technical revolution to the current microelectronic VLSI industry. There are many different strategies for future nanoelectronics [5]. For example, nanolithography technologies (such as X-ray lithography, e-beam lithography, ion-beam lithography) can be used for the line patterning in VLSI fabrication to achieve resolution in nanometer range. But this strategy still belongs to traditional top-down fabrication strategy. Another category of nanofabrication utilizes individual atoms and molecules to construct nanoelectronics circuits, which belongs to a brand new bottom-up self-assembly strategy. For example, dip-pen nanolithography (DPN) uses nano-ink with individual atoms in it to directly draw pattern on substrate. Other new transistors structures and nanoelectronics circuits based on quantum-dot cellular automata (QCA) [6], single-electron transistors (SETs) [7], spin electronics [8], carbon-nanotube (CNT) based transistors [9], nanowire cross-bar nanoelectronics circuits [10], bioelectronics [11] have also been proposed. Nanoelectronics may use totally different architecture from traditional microelectronics circuits, and their working principle may be totally different from current VLSI circuits. Nanoelectronics is bringing another technology revolution to current VLSI industry. As a result, nanoelectronics is bringing new challenges to researchers and the industry will need a large amount of trained engineers to meet the demand for next-generation nanoelectronics. In this paper, we are going to share our experience on introducing nanoelectronics into VLSI curricula in Electrical and Computer Engineering program.

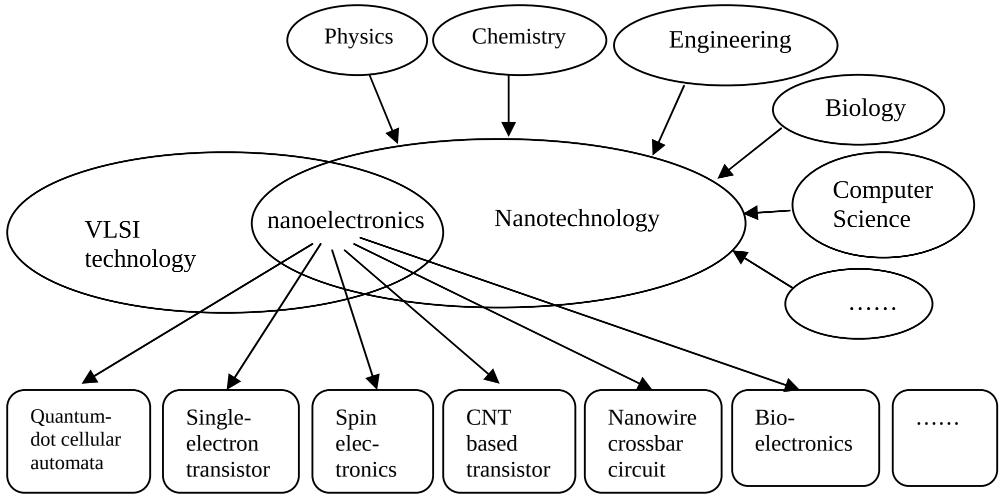

Figure 1. Interdisciplinary field of nanoelectronics

2. Current VLSI Curricula in Electrical and Computer Engineering Department

To prepare students in their VLSI career to meet the challenges of modern VLSI design, fabrication and testing, a series of VLSI courses have been developed to cover comprehensive fields in VLSI technology. These courses include but are not limited to: CPE/EE 448D - Introduction to VLSI, EE 548 - Low Power VLSI Circuit Design, EE 458 - Analog VLSI Circuit Design, EE 549 - VLSI testing, etc. The above series of VLSI curricula prepare students with knowledge background and hands-on design experience in the VLSI field. The details of the above VLSI courses are introduced as below.

2.1. CPE/EE 448D - Introduction to VLSI Design

This is an introductory course to cover the fundamentals in modern digital VLSI design. It is crosslinked as both Electrical Engineering course and Computer Engineering course. Various perspectives of VLSI design are discussed, such as MOS transistors, CMOS layouts, combinational circuit design, sequential circuit design, arithmetic building blocks, interconnect, timing analysis, clock distribution, VLSI system design and logic synthesis, design for performance, etc. This course introduces to students about fundamentals in digital VLSI circuit design and performance optimization. It serves as an introductory course in VLSI field, and prepares students for other higher level VLSI courses.

Upon completing this course, students are expected to have a comprehensive understanding about digital VLSI design, analysis and performance optimization. Students also gain hands-on experience on various VLSI EDA tools, such as PSPICE, Mentor Graphics tools (Design Architect, IC Station, Accusim), ModelSim, etc.

2.2. EE 548 - Low Power VLSI Circuit Design

With the rapid development of mobile computing, as well as the energy conservation consideration, low power VLSI design has become a very important issue in the VLSI industry. In this course, VLSI power models are introduced so that students have an in-depth understanding about the power consumption of VLSI circuits, and how we can reduce the power dissipation. A variety of low-power design methods are employed to reduce power dissipation of VLSI chips. This course is designed to cover low-power design methodologies at various design levels (from system level to transistor level). The basic low-power design strategies are introduced. Students use the learned knowledge to design low-power VLSI circuits.

Upon completion of this course, students are expected to be able to analyze the power consumption of VLSI circuits, and design low-power VLSI circuits using various strategies at different design levels. The major target is to design VLSI chips used for battery-powered systems and high-performance circuits not exceeding power limits.

2.3. EE 458 - Analog VLSI Circuit Design

Analog circuits are very important for the front and back ends to interface to the outside world. The system-on-chip (SoC) technology requires the implementation of both digital and analog modules on a single chip. The goal of this course is to introduce the modeling, design and analysis of analog CMOS VLSI. The students design analog VLSI layouts, extract the netlists and simulate the circuit behavior. The transistor sizing in analog VLSI layouts is also discussed.

Upon the completion of this course, students are able to design and analyze basic analog and mixed-signal CMOS VLSI circuits. They get to know various analog/mixed-signal VLSI circuits such as current sources and sinks, amplifiers, S/H circuits, switching-capacitance circuits, analog-to-digital and digital-to-analog converters, etc. They are expected to be able to design analog VLSI layouts, decide transistor sizing, and simulate the designed VLSI circuits.

2.4. EE 549 - VLSI Testing

As VLSI continues to grow in its complexity, VLSI testing and design-for-testability are becoming more and more important issues. This course covers VLSI testing techniques such as such as VLSI fault modeling (stuck-at-fault), automatic test generation, memory testing, design for testability (DFT), etc. VLSI scan testing and built-in self-test (BIST) are also covered. Students learn various VLSI testing strategies and how to design a testable VLSI circuit.

The goal of this course is to help students get familiar with knowledge and skills in VLSI testing and validation. Students learn VLSI fault modeling, testing strategies for combinational/sequential circuits, memory, and analog circuits. Some important topics such as delay testing, design for testability (DFT), built-in self-test (BIST) and boundary scan standard are also discussed. Upon completion of this course, students are expected to be able to effectively test VLSI systems using existing test methodologies, tools and equipments.

3. Introducing Nanoelectronics into VLSI Curriculum

Students in our VLSI program will have an opportunity to learn the design, simulation and testing of modern VLSI systematically. As VLSI technology is moving from microelectronics era into nanoelectronics era, there is a pressing need to train more students as qualified researchers and engineers to meet the requirement of next-generation VLSI technology. We mainly introduce nanoelectronics systematically in two courses in our VLSI curricula, which include EE 448 - Microelectronic Fabrication and EE 451 - Nanotechnology. However, the discussion of nanoelectronics is not limited in these two courses. We also cover the field of nanoelectronics in other VLSI courses as well.

a). In EE 548 - Low Power VLSI Circuit Design, we also introduce how power consumption can be greatly reduced in nanoelectronic circuits. We introduce Quantum-dot Cellular Automata (QCA) circuit as an example of extremely low power nanoelectronics architecture. In a QCA circuit, QCA cell polarity instead of voltage levels is used to represent “0” and “1” state. As a result, there is no current flowing in a QCA circuit, hence its power consumption is extremely lower than current CMOS VLSI circuit.

b). In CPE/EE 448D - Introduction to VLSI Design course, we also introduce the working principle and design strategy of carbon nanotube transistor based nanoelectronic circuits. In order to understand the working principle of such circuits, students need to have a clear understanding about the physical model and basic working mechanism of a carbon nanotube based transistor. We introduce to students the working principle of such CNB based transistor, and compare it to the behavior of a modern CMOS transistor to see the similarity and difference between them.

c). In EE 549 - VLSI testing course, we also introduce the testing strategy for future nanoelectronic circuits based on nanowire crossbar architecture. Nanowire crossbar structure is a promising architecture for future nanoelectronic circuits due to its fault tolerance and easy programmability. However, due to limited controllability in nanowire growth, there may be many defects in the nanowire crossbar structure during its bottom-up self-assembly. Thus the testing of such nanowire crossbar circuits can be very challenging and its testing strategy can be totally different from current CMOS VLSI circuits. The testing of future nanowire crossbar circuits is discussed in the VLSI testing course.

3.1. EE 451 - Introduction to Nanotechnology

This course aims at offering students a comprehensive overview about nanotechnology, its most recent research frontiers and applications. Nanotechnology is the science and engineering involved in the design, synthesis, characterization and application of materials and devices with the size in nanometer (10^{-9}m) scale. As a newly emerged exciting high-technology, it has attracted intensive interest and heavy investments around the world. Nanotechnology is a general-purpose technology which will have significant impact on almost all industries and all areas of society. It can offer better built, longer lasting, cleanser, safer and smarter products for home, communications, medicine, transportation, agriculture and many other fields. This course will cover basic concepts in nanoscience and nanotechnology. The textbook used in this course is listed in [12]. The goal of this course is to introduce to students the general concepts/terminology in nanoscience and nanotechnology, as well as their wide applications. Upon finishing this class, student will have a clear understanding about basic concepts in this field, such as carbon nanotube, nanowire, bottom-up self-assembly, molecular electronics, molecule manipulation, etc. In this course, we also introduce to students about nanoelectronics – using nanotechnology for next generation VLSI circuits.

3.2. EE 448 - Microelectronic Fabrication

This course covers basic microelectronic fabrication processes for semiconductor and VLSI technologies, including photolithography, plasma and reactive ion etching, ion implantation, diffusion, oxidation, evaporation, vapor phase epitaxial growth, sputtering, and CVD. Advanced processing topics such as next generation lithography, MBE, and metal organic CVD are also introduced. The physics and chemistry of each process are introduced along with descriptions of the equipment used for the manufacture of integrated circuits. The integration of microelectronic fabrication processes for CMOS and bipolar VLSI circuits is introduced. Furthermore, the fabrication of MEMS (Microelectronical Systems) and nanotechnology devices is also discussed. The fabrication of next-generation nanoelectronic circuits is introduced.

There are two strategies for fabrication of nanoelectronic circuits. One is the top-down fabrication strategy utilizing nanolithographies to achieve nanometer resolution, such as X-ray lithography, e-beam lithography, ion-beam lithography, etc. Another strategy utilizes bottom-up self-assembly to integrate individual atoms and molecules into nanoelectronic circuits, such as quantum-dot cellular automata (QCA) [6], single-electron transistors (SETs) [7], spin electronics [8], carbon-nanotube (CNT) based transistors [9], nanowire cross-bar nanoelectronics circuits [10], bioelectronics [11] etc. For each category of nanoelectronics, we introduce their working principle, design and fabrication in details. We also assign some homework and projects for students to practice these nanoelectronic circuits. Students learn from these practices and this helps them to have a deeper understanding about the future nanoelectronics. They also accumulate hands-on experiences on the EDA tools about the design and simulation of nanoelectronics, which prepare them for their future career as nanoelectronics engineers or researchers in nanoelectronics field.

For example, in the Nanotechnology class, we assign a course project about the design and simulation of an 8-bit QCA full adder. QCA Designer software (Version 2.0.3) [13] by University of British Colombia is used for this project. Quantum-dot Cellular Automata (QCA) is an attractive solution leading to more powerful computing with faster microelectronics. Since QCA circuit is a newly-emerged technology, the circuit design is not covered in details in the textbook. We mainly utilize research papers [14][15] and QCA Designer software manual [13] to teach students in this project. QCA Designer is new software and most students have never used it before. We developed detailed tutorial to help students get familiar with the software and QCA circuit design. A student's schematic design of one-bit QCA full adder circuit in the course project is shown in Figure 2. As shown in Figure 2, a QCA circuit consists of QCA cells constructed from four quantum dots arranged in a square pattern. QCA cell is loaded with two extra electrons which tend to occupy the diagonals of the cell. A QCA cell utilizes its two possible polarizations to represent "0" and "1" states. Since QCA cells operates using Coulomb interaction, no current flows between cells hence no power is dissipated. It utilizes the propagation of cell polarity instead of current to transfer signals. QCA circuits work with extremely fast speed (1~10 THz) and low power consumption. Due to extremely small size of quantum dots, QCA circuits are also 100 times denser than current CMOS VLSI circuits. Students enjoy this project because they learn the design and simulation of a nanoelectronic circuit which is totally different from traditional CMOS VLSI circuit.

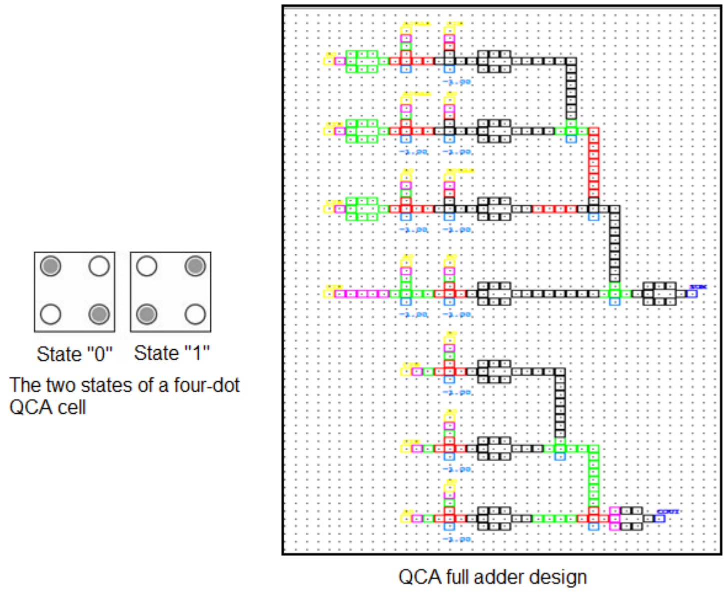

Figure 2. A full adder circuit design with QCA (Quantum-dot Cellular Automata)

4. Results and Discussions

The EE 451 - Nanotechnology course has been developed since 2008. It is integrated with already existing VLSI curricula in our Electrical and Computer Engineering department. We not only cover the nanoelectronics systematically in the Nanotechnology course, but also introduce nanoelectronics in each VLSI course as well. In this way, students have a chance to get information about the next generation nanoelectronics in any of our VLSI courses. Upon completion of these nanoelectronics related courses, many students did their master project/thesis research in the field of nanoelectronics. Based on the research results, we are in the process of publishing papers and posters in various academic conferences. Many students also plan to continue their future career in the nanoelectronics circuits. Some of them continue their Ph.D study in the nanoelectronics field. Some others have found or plan to find jobs in the VLSI industry in the nanoelectronics direction.

5. Conclusions and Future Work

In this paper, we share the experience of introducing nanoelectronics in VLSI curricula at our Electrical and Computer Engineering department. We have developed a series of VLSI curricula which include CPE/EE 448D - Introduction to VLSI, EE 548 - Low Power VLSI Circuit Design, EE 458 - Analog VLSI Circuit Design, EE 549 - VLSI Testing, etc. We systematically introduced the design, simulation, analysis and fabrication of future nanoelectronics circuits mainly in two courses: EE 451 - Nanotechnology and EE 448 - Microelectronic Fabrication. We covered different implementation strategies for future nanoelectronic circuits, such as nanowire crossbar circuit architecture, carbon-nanotube based nanotransistor, single-electron transistor, spintronics, quantum computing, bioelectronic circuits, etc. Students show intense interests in these exciting topics. Some students also choose nanoelectronics as their master project/thesis research topics, and perform successful research in the field. The program has attracted many graduate students into the field of nanoelectronics.

In the future, we plan to further develop a new course specifically about Nanoelectronics. In this class, students can do some in-depth course projects in nanoelectronics field, and further their knowledge and skills to prepare them to meet the challenges as future nanoelectronics engineers or researchers.

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