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TEACHING NANOTECHNOLOGY BY INTRODUCING CROSSBAR-BASED ARCHITECTURE AND QUANTUM-DOT CELLULAR AUTOMATA

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ABSTRACT

The end of photolithography as the driver for Moore's Law is predicted within seven to twelve years and six different emerging technologies (mostly nanoscale) are expected to replace the current CMOS-based system integration paradigm [1]. As nanotechnology is emerging, (1) there is a strong need for well-educated nanoscale systems engineers by industry, and (2) research and education efforts are also called to overcome numerous nanoscale systems issues. This paper is to propose a way to teach nanotechnology by introducing two emerging technologies: Crossbar-based Nano-Architecture and Quantum-Dot Cellular Automata.

1. INTRODUCTION

From 1960's, microelectronics have been extensively developed on CMOS (Complementary Metal Oxide Semiconductor) technology and photolithographic fabrication methodology. According to the Moore's Law, the number of transistors in a CMOS chip doubles every 18 months. The most advanced CMOS fabrication processing technology uses feature size of $65nm$, currently. As CMOS technology scales down, numerous problems result in such as extremely high power consumption, heat dissipation and unreliability. Also, it is anticipated that no more scaling will be eventually possible due to physical limitation of photolithography.

Since 1990's, various researches have been performed on nanotechnology to supersede CMOS technology. According to the ITRS 2004, six major nanotechnology thrusts have been identified to emerge [1]. Among the new nanoscale technologies, crossbar-based nanoscale architecture and quantum-dot cellular automata (QCA) have some outstanding advantages [2, 3].

In crossbar-based nanoscale architecture, a two dimensional array (nanoarray) formed by the intersection of two orthogonal sets of parallel and uniformly-spaced nanometer-sized wires [2, 4], such as carbon nanotubes (CNTs) and silicon nanowires (SiNWs). Experiments have shown that such wires can be aligned to construct an array with nanometer-scale spacing using a form of directed self-assembly. It is to achieve ultra-high density which has never been achieved by photolithography (a density of 10^{11} crosspoints per $1cm^2$ has been achieved [5]). A 4×4 nanoscale crossbar with decoder structure is shown in Figure 1.

In addition, QCA can provide not only nanoscale system implementation, but also a new way of computation and information transformation. It is predicted that the density of QCA could exceed 10^{12} devices per $1cm^2$ and the operating speed could reach THz domain [6]. Compared with conventional CMOS-based digital logic, QCA hold its logic

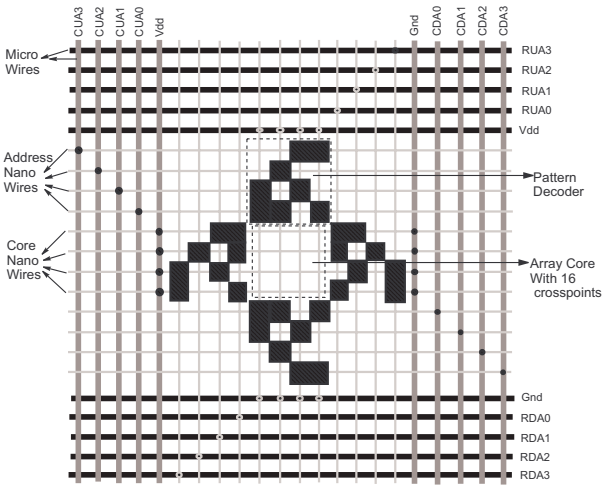

Figure 1. A 4×4 nano-crossbar with imprinted pattern decoder

state by the position of electrons instead of voltage level [7, 8]. Also, the information transformation is realized by Coulomb interaction between adjacent QCA cells and the power dissipation is extremely low compared with CMOS technology. An 2-out-of-3 threshold gate with hysteresis behavior is shown in Figure 2, for example.

Although there is a strong need for education and research in nanotechnology, both undergraduate and graduate-level courses of today's science and engineering curricula usually do not properly include topics related to it. In this paper, we will propose a way to teach nanotechnology by introducing crossbar-based architecture and QCA in both undergraduate and graduate levels.

2. EDUCATION TOPICS FOR CNT/SINW CROSSBAR-BASED ARCHITECTURE

In the following, the topics identified as suitable for teaching crossbar architecture are listed.

1. *Nanoscale devices based on CNT and SiNW:* First of all, it is important to teach characteristics of nanoscale materials such as CNT and SiNW. Then, devices based on CNT and SiNW should be introduced. The following topics are recommended.
   (a) *FET (Field Effect Transitor) devices:* Lieber et al have shown electro-mechanical switching devices

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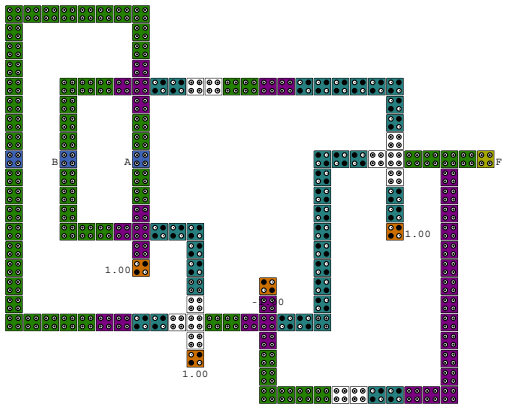

Figure 2. Sample QCA gate: 2-out-of-3 threshold gate with hysteresis behavior.

using suspended nanotubes [4]. The NT-NT junction is bistable with an energy barrier between the two states. Doped SiNWs and CNTs exhibit FET (Field Effect Transistor) behavior [2].

(b) *Interconnect:* Both CNT and SiNW can be used as interconnects along with microscale metallic wires.

(c) *Memory devices:* One of more crosspoints can be used as memory devices, as well. Structures and operation principles can be discussed.

2. *CNT and SiNW crossbar structures:* Multiple CNTs and/or SiNWs can be assembled to form a crossbar structure, so that crosspoints can be used as storage or logic devices. Design and assembly issues can be demonstrated.
3. *Nano-Micro interface:* Most of currently proposed crossbar-based architectures also include microscale devices and interconnects. Thus, nano-micro interfacing methods should be taught.
4. *Defect and fault tolerance:* In nano-crossbar systems, various defects and faults that are fully different from the ones found in CMOS technology are expected. Thus, defect and fault-tolerant issues should be discussed and possible techniques should be taught.
5. *Stochastic directed self assembly algorithms:* Nano-crossbar systems can be fabricated by directed self assembly. Stochastic assembly algorithms can be also discussed.
6. *Design automation:* Various design automation issues associated with nano-crossbar systems are to be addressed as well.

3. EDUCATION TOPICS FOR QUANTUM-DOT CELLULAR AUTOMATA

In the following, the topics identified as suitable for teaching QCA are listed.

1. *QCA cell structure:* Multiple quantum dots can be used to form a QCA cell. Then, two or more electrons can be placed. QCA hold its logic state by the position of electrons.
2. *Bi-stable behavior of QCA cell:* Due to the Coulomb repulsion, the two electrons can be only in the diagonal vertex. So the two different polarization states can represent logic 0 and logic 1.
3. *Cell-to-cell electrostatic interaction:* The polarization of one cell will be directly affected by the polarization of its neighboring cells. This interaction is known to show non-linear cell-to-cell response. Both intra and inter-cell behaviors can be discussed.
4. *QCA devices:* Multiple QCA cells can be placed strategically to form logic devices such as MV (Majority Voter) and INV (Inverter). Various QCA logic gate can be introduced.
5. *4-phase clocking:* Presently, all QCA circuit proposals require a clock not only to synchronize and control information flow but the clock actually provides the power to run the circuit. The concept of clocking for QCA, referred to as the four-phase clocking, has been introduced in [9]. The four-phase clocking scheme emulates classical shift register behavior since a binary digit of information can be stored in each cell's latched polarization.
6. *QCA floor planning:* In QCA, floor planning is very important due to the fact that "layout=timing" [9]. Numerous floor planning techniques can be taught.
7. *Design automation:* Various design automation issues associated with QCA systems can be discussed as well.

It is desirable to teach aforementioned nanotechnology topics in existing design courses for a week or two. Small projects or lab experiments can be also given for in-depth education.

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