Fabrizio Lombardi
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Editors

DESIGN AND TEST OF DIGITAL CIRCUITS BY QUANTUM-DOT CELLULAR AUTOMATA

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Preface

Emerging technologies have been a topic of great interest over the last few years; as predicted by the Technology Roadmap of the Semiconductor Industry, CMOS as today's dominant technology for manufacturing computer systems by Very Large Scale Integration (VLSI) will be encountering serious hurdles in the future. The projected expectations in terms of device density, power dissipation and performance necessitate radically different technologies that provide innovative solutions to integration as well as computing. So-called emerging technologies have been advocated from disparate sources (both industry and academia) to meet these ambitious objectives, while realizing the ever-higher demands posed by the ubiquitous nature of computing in modern society.

This book addresses one of the most interesting among emerging technologies for digital design, Quantum-dot Cellular Automata (QCA). Over the last few decades since its inception at the University of Notre Dame, QCA has dramatically evolved in a dynamic and exciting field of investigation with contributors from all over the world. QCA is a challenging technology that due to its unique structural and operational features represents a revolutionary departure from current practice. QCA relies on principles that are fundamentally different from CMOS and therefore, it may offer unprecedented advantages to solve those challenges that are expected to occur at the end of the technology roadmap. For example, as its operation is based on Coulombic interactions, designers of QCA-based circuits must be made aware of the implications that selective properties (such as those based on switching and clocking) may come into play once a QCA circuit is embedded on a planar layout.

Numerous journal and conference articles have appeared in the technical literature; the last few years have also seen an increased number of professional meetings in which many sessions have been devoted to advances in QCA. However, QCA necessitates an understanding of physical and electrical phenomena that are not readily available from a single source. This book provide a focused reference by which up-to-date topics are treated in detail with direct impact on research and practical implementations; moreover, its contents reflect an interdisciplinary approach by which scientists and engineers can mutually benefit. Only essential mathematics and physics are presented, while devoting substantial coverage to design and manufacturing issues as well as related topics such as testing, defect modeling and performance.

In this book, we have combined topics that cover the whole spectrum of interests in QCA: starting from a basic characterization at device-level, circuits and modular digital systems (such as memories and universal logic) are introduced to the reader within a systematic and intuitive presentation that include examples as well as comparison metrics. The organization is structured such that starting with an introduction to emerging technologies, up-to-date fundamentals of QCA are reported to engage the reader into the most recent advances of this field as reflected in the detailed treatment of sequential and combinational QCA circuits. The main emphasis is, however, on design and test to include digital QCA circuits and models for characterizing among the many attributes power consumption, defect diagnosis, modularity and fault tolerance. QCA can encompass multiple desirable features within different technological frameworks (based on metal as well as molecular implementations) and new computational paradigms (such as processing-by-wire and storage-by-motion).

The material covered in the chapters requires a basic understanding of physics, mathematics and electrical/electronic engineering, as commonly made available in an undergraduate degree program. This book can therefore be used as a reference as well as textbook for senior elective and graduate courses in nanotechnology, with an emphasis on emerging technologies. Advanced researchers will also find this book interesting as it provides a detailed treatment of QCA and issues involved in integrating basic device functionalities (combinational and sequential) into working circuits and systems. Novel research directions in QCA are also provided for the interested technical investigator. The authors of each chapter have an in-depth knowledge of QCA as reflected in their studies and work experience; this book is the result of the authors' research and development in QCA over more than five years as supported by federal agencies and industrial partners.

This book has been made possible by the collaboration of all authors; also, the authors would like to acknowledge enlightening discussions with Craig Lent (University of Notre Dame), Doug Tougaw (Valparaiso University), Konrad Walus (University of British Columbia), Cecilia Metra (University of Bologna), Salvatore Pontarelli (University of Rome Tor Vergata), Marya Libermann (University of Notre Dame), Niraj Jha (Princeton University), Hamid Hashempour, Sanjukta Bhanja (University of South Florida) and Jose Fortes (University of Florida). Their

insights and comments have been a tremendous encouragement for us to pursue the publication of this book.

Comments on this book can be sent to the editors by electronic mail: Jing Huang (hjing@ece.neu.edu) and Fabrizio Lombardi (lombardi@ece.neu.edu).

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Chapter 1

Introduction

J. Huang, M. Momenzadeh, and F. Lombardi

In the last few decades, the exponential scaling in feature size and increase in processing power have been successfully achieved by conventional lithography-based VLSI technology. However, this trend faces serious challenges due to fundamental physical limits of CMOS technology such as ultra-thin gate oxides, short channel effects, doping fluctuations and increasingly difficult and expensive lithography at nano-scale regimes. It is projected that the scaling process of known-today CMOS technology will end by the channel length of 7 nm by 2019 [1]. There has been extensive research in recent years at nano-scale to supersede conventional CMOS technology. It is anticipated that these technologies can achieve a density of 10^{12} devices/cm^2 and operate at THz frequencies [2].

Nanotechnology provides new possibilities for computing due to the unique properties that arise at such reduced feature sizes. Among these new devices, *Quantum-dot Cellular Automata* (QCA) [3] [4] relies on new physical phenomena (such as Coulombic interactions), and innovative techniques that radically depart from a CMOS-based model. QCA not only gives a solution at nano-scale, but it also offers a new method of computation and information transformation [5] [6]. Consider the processing features of CMOS systems: some circuits (i.e., logic gates) perform computation, while others (i.e., wires) are used for signal/data transfer and communication. In contrast, *computation and communication* occurs simultaneously in QCA [5]. QCA uses two basic logic gates, namely the INV and Majority Voter (MV). QCA is very promising because with this technology, computational paradigms which radically depart from traditional CMOS, can be implemented [7] [8] [9]. QCA design involves diverse and new paradigms such as *memory-in-motion* and *processing-by-wire* [7] [10]. Memory-in-motion is an instance of the more general paradigm of processing-by-wire. Processing-by-wire (PBW) [10] is the QCA capability by which information manipulation can be accomplished, while transmission and communication of signals take place. PBW capabilities can be observed in the so-called inverter chain as well as in the arrangement of the cells in an MV. Besides the extra-high density feature, QCA can provide ultralow power dissipation and true power gain [11] [12] which are very promising due to the high density of this nano device. Recent development in QCA manufacturing involves molecular implementation. It is expected that molecular QCA will be manufacturing using DNA self-assembly and/or large scale cell deposition on insulated substrates [13].

1.1 CHALLENGES

The small size of QCA-based systems combined with their manufacturing methods (such as self-assembly) are substantially different from CMOS and make them more susceptible to defects and faults. In addition, defect in QCA manufacturing may well manifest themselves differently at logic level than CMOS. Defect characterization is therefore vital to design and test of QCA systems.

One of the fundamental issues in the testing community is the radical shift in computation and fabrication technology and its effect on the test flow. Do test generation and design-for-test become even intractable? Since the manufacturing process for nano devices is ill-defined, it is extremely difficult to address manufacturing testing problems. However, it would be inappropriate to ignore testing of these devices until the manufacturing state. QCA has the capability to provide defect tolerant operation and architectures that avoids massive logic redundancy or post-fabrication configuration. For QCA, placing individual cells on specific location on the substrate is difficult, and various types of cell misplacement defects may occur (such as cell misalignment, missing cell, or additional cell). These defects can have a substantial effect on the functionality of the device and hence the circuit. So proper testing of these devices for manufacturing defects plays a major role for quality of QCA-based circuits. Since the basic logic elements of a QCA-based design are different from conventional CMOS design, they need different testing schemes.

Moreover there are other manufacturing defects (such as faults in the clocking circuitry and the I/O mechanism) that may not occur during cell synthesis phase (in which the individual cells or molecules are manufactured) or deposition phase (in which the cells are placed in a specific location on the surface). Some of these faults