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Physics, technology and applications

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**Rutu Parekh**
*VLSI and Embedded Systems Group, Dhirubhai Ambani Institute of Information and Communication Technology (DA-IICT), Gandhinagar, India*

**Rasika Dhavse**
*Department of Electronics Engineering, Sardar Vallabhbhai National Institute of Technology (SVNIT), Surat, India*

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*Dedicated to my beloved parents*

*Who have been my constant inspiration, throughout my life*

—Rutu

*To Neeraj and Aryaa—the rock-solid pillars of my life*

*—for their encouragement, confidence and patience*

—Rasika

# Contents

# Preface

## Philosophy and goals

Welcome to the amazing world of nanoelectronics! Nanoelectronics holds some answers as to how we can increase the capabilities of electronics devices while reducing their weight and power consumption. The International Technology Roadmap for Semiconductors (ITRS) predicts the technical capability the industry needs to continue to meet Moore's law. For several decades, planar CMOS technology has been the workhorse for integrated circuit (IC) designers. It has been scaled as per Moore's law, resulting in ever decreasing device sizes and numbers of technology nodes, the present standard being 10 nm. The ITRS predicts that the end of metal-oxide-semiconductor field-effect transistor (MOSFET) scaling will arrive in 2024 with a 7.5 nm process. Getting to 7.5 nm, however, presents some long-term difficult challenges.

The future of electronics lies with nanoelectronics. This is a completely interdisciplinary field. Knowledge in the area of semiconductor physics, electronics, circuit design, material science, quantum physics, nanofabrication, modelling and simulation is required to understand, design and fabricate a heterogeneous IC. Nanoelectronics promises a myriad of possibilities, from high-speed computing to advanced medical treatments, and even the potential for new forms of energy production. The applications of nanoelectronics can be found in diverse fields such as quantum computing, advanced memory, wearable and flexible devices, display technology, spintronics, optoelectronics, etc. It aids in developing miniaturized portable electronics that has no counterpart in present technology. To design a circuit for such a purpose, one needs to understand the device, its physics and fabrication process, as well as its limitations.

This book provides insight into the future of electronics, emerging devices, logic and memory, sensors and system architecture, in addition to nanofabrication. In order to understand the electrical characteristics and design parameters, it is vital to know the fundamental physics behind them. That understanding is developed in the subsequent chapter contents. With this knowledge, the reader will be capable of understanding the applications and design principles of a given device or sensor. This book can be offered as a textbook for masters or undergraduate students, researchers, engineers and specialists in various fields including electron devices, solid-state physics and nanotechnology.

We would like to emphasise that, since there is no such book that bridges the gap between nanoscience, nanofabrication, nanodevices, their circuit design and applications, the present book is written to address this. As far as subject depth is concerned, it cannot easily be quantified; but as experienced researchers and academicians in this area, we think we have made fair decisions and written chapters bearing in mind this aim of linking the fields of nanoelectronics at all times. It is very clear that hybrid circuit design requires knowledge in order to establish and grasp the relation between physical and electrical parameters. This book is intended in particular for engineering students, who can hopefully then begin to explore this new revolutionary technology and use it for the betterment of humanity.

## Prerequisites

The prerequisites for this subject are college-level mathematics, an introduction to modern physics and knowledge of electronic circuits. We thus propose that this book is for senior-level undergraduate/graduate or beginner-level research students who wish to embark on a journey into the field of nanoelectronics. Nanoelectronics begins where conventional devices fail. As such, we will cover the limitations of the current technology and connect the same to subsequent chapters/topics. Also, it is not compulsory to teach the whole book in a single semester: the tutor can selectively decide on a topic as per their choice.

## Organisation

This book is organised into nine chapters, each covering a specific area. **Chapter 1, Physical and technological limitations of nano-CMOS devices to the end of the roadmap and beyond**, focuses on the scaling trend, the “red brick wall” encountered by present nano-CMOS technology and the role of ITRS. In order to delay the absolute failure of CMOS technology, emerging devices are being developed which can be hybridised with present CMOS technology and potentially replace CMOS. A brief description of emerging and prototypical logic and memory devices is presented in brief. These devices contain the potential to revolutionise the future of electronics, and present possible advantages that have no CMOS counterpart. The chapter provides an in-depth insight into the impact of these technological options and their applications.

**Chapter 2, Introduction and overview of nanoelectronics**, is aimed at giving an introduction and overview of nanoelectronics and its applications. The revolution and continued evolution in this field is presented with a short history. The market potential and its requirements are further discussed, as the field is growing with ever increasing potential in the current time. This chapter also covers nanofabrication and its two approaches, top-down and a bottom-up approaches, utilising different methods. The primary goal is to establish a link between the market potential, what the technology and fabrication can offer, and the kind of applications that can be foreseen.

**Chapter 3, Introduction to the quantum theory of solids**, provides a brief review of a few concepts from classical Newtonian physics, and how this fails to explain phenomena at the nanoscopic scale. As is detailed within, the classical mechanical model is able to describe all observed physical phenomena; however, when it comes to the nanoscale this model breaks down, because the properties of the materials change dramatically. At this scale, the surface-to-volume ratio increases, gravitational forces become negligible and random molecular motion becomes more important. This changes the properties of the material and affects the devices that are fabricated at this scale. It is hence necessary to develop a new model that can explain such physical phenomena. This has led to a new branch of physics, i.e. quantum physics (QP) or quantum mechanics, which is able to explain the behaviour observed at nanoscale. QP enables us to explain phenomena such as the photoelectric effect, Compton effect. etc. In this chapter, we introduce quantum mechanics and how it evolved in the late 19th and early 20th centuries. Further, light's behaviour as a particle as well as a wave is described by the photoelectric effect and Young's double-slit experiment, respectively. Further, the dual nature of the particle is explained using the de Broglie principle. Schrodinger's equation is then explained, which gives the probability of finding a subatomic-scale particle at a certain position in a quantum well.

In addition to the formulation of Schrodinger's equation, its solution, the concept of a potential well, the characteristics of the wave function and its interpretation and significance, and, finally, the application of Schrodinger's equation in the structure of an atom form subsequent parts of this chapter. The equation serves as a basis with which to understand band theory. Band theory explains the difference between conductors, insulators and semiconductors. Materials are distinguished according to the differences in their band gaps. Adding impurities or varying temperature changes the band gap in semiconductors, which consequently changes the properties of the semiconductor and its electrical conduction. One more important measure to understand and exploit the properties and behaviour of materials is Fermi–Dirac statistics. It is useful to acquire the probability of electrons at a given energy level at a specific temperature. These concepts can be utilised by physicists and chip makers to make more energy-efficient devices. Hence, this chapter details the fundamentals of quantum physics and how they relate to the electrical properties of nanodevices.

An overarching goal of **chapter 4, Emerging research devices for nanocircuits**, is to survey, assess and catalogue viable emerging devices. With the evolution of the roadmap from the ITRS to the International Roadmap for Devices and Systems (IRDS), an expanded focus on systems requires that one evaluates the applicability of these novel devices to new types of systems and architectures. This goal is accomplished by (a) extending MOSFETs to the end of the roadmap, (b) employing "beyond CMOS" charge-based non-conventional field-effect transistors (FETs) and other charge-based information carrier devices, and (c) developing alternative information processing devices. Under these categories various devices, like carbon nanotubes (CNTs) and graphene-based devices, channel replacement devices, tunnel FETs, single-electron transistors, nanoelectromechanical (NEMS) systems and many more, are explained based on their physics and from a circuit application and design point of view.

With great progress being made in emerging memory technologies, the current trends and limitations are first discussed in **chapter 5, Emerging memory devices**. For the past three and a half decades of their existence, the family of semiconductor memory devices has expanded greatly and achieved higher densities, higher speeds, lower power, more functionality and lower costs. Despite its limitations, the field of conventional semiconductor memory continues to flourish, and memory device scientists are finding ways to meet these technical challenges, possibly even leading to the development of a 'universal memory' with low cost, high performance and high reliability for future electronic systems. In this chapter emerging memory devices, such as ferroelectric RAM, magnetoresistive RAM (MRAM), Mott memory, molecular memory, macromolecular memory and resistive RAM, are detailed with their physics, working and applications.

For accurate projections and evaluations of device performance in the nanoscale era, it is of utmost significance that materials, processes and devices should be modelled precisely. Indeed, modelling and simulation of nanoscale processes and devices has become an exciting topic of research today. However, when working with emerging memory or logic devices, very few commercial simulators are available. In **chapter 6, Simulation and modelling**, we give our readers a detailed account of modelling and simulation using Technology Computer-Aided Design (TCAD) tools. Multiphysics environments in which to implement MEMS/NEMS devices are outlined and methodologies demonstrating novel nanoelectronic devices with CMOS technology are also illustrated. At the end of this chapter, the reader is supplied with references to these tools for their further perusal, based on their research interests.

Synthesis at the nano level, i.e. nanofabrication, represents a gigantic leap that has brought the world of ultra-small things into reality. In fact, nano evolution is possible due to systematic progress in microfabrication, nanofabrication, thin-film synthesis, CNTs, microelectromechanical-NEMS technologies, process integration at the nanoscale and nanopackaging. All these aspects of fabrication at the nanoscale are explored in **chapter 7, Nanofabrication.**

Modern computer architecture is based on von Neumann architecture and has continuously improved, as per Moore's law. However, this scaling trend has reached its fundamental physical limit with today's architecture and materials. Much reduction in area and power demand can be achieved if a single device can be exploited as *both* a memory and logic device. **Chapter 8, Emerging architecture**, focuses on the various architectures that are being developed in the field of emerging memory devices. The architectures introduced are 3D integration of FPGAs, CMOS-based field programmable nanowire interconnects, nano-crossbar arrays, nanomagnetism-based MRAM and spin-torque transfer RAM. Furthermore, the next wave of architecture aims to mimic the human brain, which is emerging in neuromorphic and cortical architectures.

After giving a detailed account of fundamental nanoscale phenomena, devices, processes and architectures, we present the highly active and 'in demand' arena of nanosensors and transducers. This stream converges with many other streams such as chemistry, physics, biology, engineering and technology at the nanoscale and is becoming an altogether new discipline, rich with endless possibilities. Reading **chapter 9, Nanosensors and transducers**, should stimulate the readers' grey matter and help further their creativity and skills in the development of newer, smaller, lighter, cheaper, more accurate and more power efficient products.

To conclude, this book acts as an A-to-Z of topics in the field of nanoelectronics. The contents are organised such that the reader will be able to easily establish a link between device physics, systems, design, modelling, simulation and fabrication, and to gain an insight into the prospect of a particular technology. Nanoelectronics is full of exciting applications, and we are sure that it has a potential to solve the "big ticket" problems faced by mankind.

## Notes to the readers

We want senior undergraduate engineering students to be equipped with knowledge of the rich and unending potential of nanoelectronics. They should know the different devices that can overcome the limitations of conventional CMOS technology, their underlying physical mechanisms, their models, fabrication techniques and the tools which can be used to model these devices. They should get an idea of the circuits and architectures that can be built in implementing these new devices. In most universities, the course curricula include all these topics, and professors and students have to refer to a number of books. Our own experience is the same. That is the very reason why we are here trying to provide a one-point solution. In this, the reader should bear in mind that this is a continuously evolving technology. Chapters can be covered and skipped as per the curriculum and need of time.

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Our hearts and souls feel greatly honoured to find this opportunity to be in thankfulness before almighty for his constant innumerable blessings and also for bestowing us with enough strength and courage to complete our book.

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# Author biographies

## Rutu Parekh

Dr Rutu Parekh received an M.Eng. in Electrical Engineering from Concordia University, Montreal, Canada, a PhD in Electrical Engineering (Nanoelectronics) from the Université de Sherbrooke, Sherbrooke, Canada, and worked as a Postdoctoral fellow at Centre of Excellence in Nanoelectronics, IIT Bombay in 2015. Her research areas are ASIC design, micro/nanoelectronics, nanofabrication, embedded systems and IOE. She has research experience at the École Polytechnique de Montréal, industrial experience with eInfochips, Ahmedabad, India and HP Karkland, Montreal, and teaching experience with Nirma University of Science and Technology, Ahmedabad. She is also associated with The Inter-University Centre for Astronomy and Astrophysics, Pune, India, as a Visiting Associate. She is currently working as an Associate Professor at DA-IICT, Gandhinagar, India. She has published a number of international journal and conference articles related to her research areas. In addition, she has been offering her services as an editorial board member for international journals and as a technical committee member in numerous international conferences. She is founder and Chair of the IEEE Nanotechnology Council Chapter, Gujarat section, India.

## Rasika Dhavse

Rasika Dhavse is serving as Associate Professor in the Department of Electronics Engineering of Sardar Vallabhbhai National Institute of Technology, Surat. She pursued her doctoral degree in the field of nanocrystal-based flash memory devices. She has more than 25 years of academic experience. Her research students are working in the fields of nanoelectronics, rad-hard devices, sensors, VLSI design and technology, biomedical instrumentation, etc. In addition, she has successfully completed many government-funded research projects. She has organised numerous seminars, workshops, FDPs and STTPs on various topics related to VLSI design, semiconductor physics and technology, fabrication and characterization of MOS devices, nanoelectronics and nanotechnology, embedded systems, robotics, system automation, various tool trainings, etc. and has chaired many reputed international conferences. She has significant research papers to her credit. She is one of the founders and Vice-Chair of the IEEE Nanotechnology Council, Gujarat section, India.