Advanced Semiconductor and Organic Nano-techniques

I

Nanoscale Electronics and Optoelectronics

Hadis Morkoç

AP

ADVANCED SEMICONDUCTOR AND ORGANIC NANO-TECHNIQUES

Part I

Nanoscale Electronics and Optoelectronics

Editor

HADIS MORKOÇ

DEPARTMENTS OF ELECTRICAL ENGINEERING AND PHYSICS
VIRGINIA COMMONWEALTH UNIVERSITY
RICHMOND, VIRGINIA

ACADEMIC PRESS

An imprint of Elsevier

Amsterdam • Boston • London • New York • Oxford • Paris
San Diego • San Francisco • Singapore • Sydney • Tokyo

This book is printed on acid-free paper.

ACADEMIC PRESS
An Imprint of Elsevier
84 Theobald's Road, London WC1X 8RR, UK
http://www.elsevier.com

ACADEMIC PRESS
An Imprint of Elsevier
525 B Street, Suite 1900 San Diego, California 92101-4495, USA
http://www.elsevier.com

Set ISBN 0-12-507060-8
Part I ISBN 0-12-507061-6 Nanoscale Electronics and Optoelectronics
Part II ISBN 0-12-507062-4 Tunable Bandgaps and Nanotubes
Part III ISBN 0-12-507063-2 Physics and Technology of Molecular and Biotechnology Systems

A catalog record for this book is available from the Library of Congress

A catalogue record for this book is available from the British Library

Typeset by Newgen Imaging Systems (P) Ltd, Chennai, India
Printed and bound in Great Britain by MPG Books, Bodmin, Cornwall

03 04 05 06 07 MP 9 8 7 6 5 4 3 2 1

Preface

Revolutionary and evolutionary developments in microelectronics have changed our way of life, both at home and in the work place, and left nothing untouched that is of importance to mankind. The genesis of these developments can be traced back to 1947 with the invention of transistors, followed by the invention of integrated circuits (ICs) and metal oxide semiconductor field effect transistors (MOSFETs) in 1958. Ever since then, the intellectual and commercial driving forces have been in place to continually miniaturize these devices and circuits, resulting in exponential improvement trends in their performance, power requirements, and cost per function. These improvements have created a semiconductor industry that has grown to over $200 billion in annual sales. At the time of writing, the minimum feature sizes on ICs are well under 100 nm for patterned line-widths and down to about 2 nm for film thicknesses. Gate dimensions of mass-produced MOSFET devices are projected to be less than 13 nm with some 60 billion transistors per chip by the year 2013. With new lithographic tools, the clock frequency of CPUs will be boosted to 10 GHz in 2005–6, with terahertz frequency performance at the device level. To guide research and development, the industry formed the International Technology Roadmap for Semiconductors (ITRS), which projects that IC minimum patterned features should scale to about 10 nm over the next 15 years. The new realm presents deep technological and scientific challenges, as operation at the device level in these dimensions represents uncharted territory. This paradigm comes with many issues, challenges, and possible limits of further CMOS scaling beyond 100 nm. These include lithography, voltage limit, quantum mechanical tunneling, and dopant density fluctuations. It is projected that bulk CMOS will be scaled to 10-nm channel length or even lower, if gates with high dielectric constants are used along with device structures designed to maintain gate control and minimize substrate effects. In this context, one should mention silicon on insulator (SOI). Fuelled initially for its potential radiation hardness, SOI technology by itself or in a version merged with MOSFET technology is increasingly becoming a common feature in nanoscale FETs.

In parallel to scaling of more or less existing device concepts, variants of transistors are explored including single-electron transistors (SETs). Although SETs suffer from low voltage gain and high sensitivity to single charged impurities, the prospect of using hybrid SET/FET circuits in new architectures for advanced information processing is alluring. One thing is certain though, that the charge-sensing capability of SETs pave the way for many applications in the area of metrological current and capacitance standards, Coulomb blockade absolute thermometers, and perhaps fully solid-state quantum computers.

Though on a smaller scale in terms of volume as compared to Si ICs, another quiet revolution is taking place in the realm of semiconductor heterostructures that have already paved the way for very compact and efficient devices that emit light and detect IR, visible, and UV light, and amplify and receive signals. Compact optical emitters with very low power consumption coupled with detectors and fiber optics have improved long-haul and short-haul communication systems to the point where one can no longer tell the distance while conversing on the telephone. Visible light emitting diodes covering all primary colors have changed the landscape in the world of displays and indicator lights. What is more spectacular is that they are poised to make major inroads in lighting (white light). To push these devices to the ultimate, quantum dots provide a tool to engineer atom-like energy levels, offering much potential for lasers requiring very low power.

One cannot talk about microelectronics without paying homage to storage media that have grown in density, and shrunk in size and cost at a rate predicted by Moore's law, but with an impact greater than anyone could have imagined. As in the case of MOSFETs, there are very stringent scaling issues, many of which could only be dealt with by new inventions. The storage technology has advanced to the extent that non-traditional applications, or applications in the domain of other technologies are being pursued. Among these is magnetoresistive random access non-volatile memory (MRAM). It is evident that for magnetic nanotechnolgy memories to prevail, they must be able to exploit the evolving semiconductor nanotechnology. Fortuitously, MRAMs can scale to minimum dimensions of less than 0.1 μm and require relatively few masks, but with scaling come some technological difficulties that are already being faced by hard disks, because the size of a stored bit may be only 50–100 nm.

SETs have aroused intellectual interest by raising the prospects of achieving quantum computing. The field of quantum computing also encompasses applications in quantum cryptography, quantum teleportation, and quantum memory. In classical digital computing, information is digitized into binary bits, which are then manipulated according to a given set of instructions (the program) to carry out a computation. Unlike the binary systems, bits of quantum data, or qubits, hover in an undetermined state somewhere between these two values and are considered lossless, which implies instability. When this fuzzy two-state bit is plugged into a logical operation, the computer in essence computes both outcomes simultaneously. If just 300 qubits were to be coupled together, the computer would instantly compute all 2^{300} possible outcomes—approximately the same number as there are elemental particles in the universe. While there are many approaches to quantum computing already being pursued, outside of the introductory chapter, this volume deals with a narrow cross-section of that body that is realizable with semiconductors.

Despite the odds, the quantum computer continues to captivate the imagination of many scientists. A simple demonstration at the elemental level is far from being a useful quantum computer, but represents the ultimate frontier. Even though compelling arguments can be forwarded about show stoppers, our intrigue continues to propel us forward in the quest toward inventing new gadgetry, new ways of tackling both old and new problems, and attempting to uncover the greatest maze of all, the human mind. Progress has never been straightforward and will never be. There have been many false leads and many correct ones. But, this is the way it goes. It is very difficult for neophytes to accept this somewhat chaotic path. Eventually, the science corrects itself and human kind is always the beneficiary.

HADIS MORKOÇ
Richmond, VA
October 2002

List of Contributors

Numbers in parentheses indicate the pages on which the authors' contributions begin.

F. BALESTRA (325), *ENSERG, BP 257, 38016 Grenoble Cedex 1*

S. BANDYOPADHYAY (441), *Virginia Commonwealth University, Department of Electrical Engineering, Richmond, VA 23284-3072*

S. CRISTOLOVEANU (325), *ENSERG, BP 257, 38016 Grenoble Cedex 1*

D. G. DEPPE (367), *University of Texas of Austin, J.J. Pickle Research Center, Austin, TX 78758*

R. DOERING (147), *TI Senior Fellow, Texas Instruments Inc., P.O. Box 650311, MS 3730, Dallas, TX 75265*

H. HUANG (367), *University of Texas at Austin, J.J. Pickle Research Center, Austin, TX 78758*

K. LIKHAREV (239), *SUNY at Stony Brook, Stony Brook, NY 11794-3800*

H. MORKOÇ (1), *Virginia Commonwealth University, Department of Electrical Engineering and Physics Department, Richmond, VA 23284-3072*

J. P. PEKOLA (303), Low Temperature Laboratory, Helsinki University of Technology, P. O. Box 3500, 02015 HUT, Espoo, Finland

A. V. POHM (411), *Ames, Iowa 50010*

Y. TAUR (211), *University of California, Department of Electrical and Computer Engineering, La Jolla, CA 92093-0407*

Contents

Advanced Semiconductor and Organic Nano-Techniques (Part I)
H. Morkoç (Ed.)

CHAPTER 1

Emerging Advances in Microelectronics, Optoelectronics and Bioelectronics

H. Morkoç

VIRGINIA COMMONWEALTH UNIVERSITY
RICHMOND, VIRGINIA

I. Introduction

The silicon-based microelectronics revolution of the past few decades has molded our culture and become an integral part of our daily life to the point where it is taken for granted. What is also taken for granted is the reduced cost to customer per performance. This is the only industry where the consumer is used to expecting more and paying less. The omnipresent silicon microelectronics involve the use of silicon for its electronic properties. An emerging field, bio- and chemical sensors, rely mostly on silicon micromachining whereby the mechanical properties along with some electrical properties of silicon are utilized for such applications as drug delivery, biosensing, gene sorting, micropumps, etc. Though on a smaller scale in terms of volume, another revolution is taking place which is not as apparent to the non-technical consumer. Specifically, novel heterostructures based on very new semiconducting materials have paved the way for many devices that emit light, detect light, and amplify and receive signals. Compact optical emitters with very low power consumption coupled with detectors and fiber optics have improved long- and short-haul communication systems to the point where one can no longer tell the distance while conversing on telephone. Visible light emitting diodes covering all primary colors have changed the landscape in the world of displays and indicator lights. What is probably most spectacular is that they are poised to make major inroads in lighting (white light). On the electronics side, novel heterostructure devices have made it possible to amplify signals and detect immensely weak signals that led to such things as digital telephones and small direct satellite broadcast dish antennas. Indications are that the same technology is poised to bring about auto guidance and collision avoidance systems. These novel semiconductors also played an important role acting as a medium for the development of reduced dimensional systems to the point of confinement in all three dimensions at almost atomic scales. The reduced dimensional systems are conducive for quantum effects where the associated states are explored for digital logic states. While semiconductor manufacturing has continually become more efficient with tremendous savings passed on to consumers, efforts are underway to perform at least some of the functions that are traditionally in the domain of inorganic semiconductors with organic semiconductors (plastic) which are potentially very inexpensive and flexible.

On a different front, researchers are busy trying to combine the revolutions in microelectronics and biology in an effort to launch yet another revolution which will most likely produce a larger impact than either of the two just mentioned. Already available, at least in the laboratory, are genechips which rapidly identify various mutations of genes, and probes that are small enough to be implanted and control the release and amounts in drug delivery. A case in point is the delivery of insulin by measuring the glucose level. The developments in the two distinct fields also come together to produce instrumentation for analysis and diagnosis. For example, some very efficient means for gene separation rely on rapid labeling and data collection which benefited tremendously from advances in optoelectronics and electronics. Bringing to bear biochemistry and micromachining technologies on the problem of biosensing has led to a plethora of biosensors which are compact and inexpensive, and can be operated by an unskilled operator in the field. Diagnosis of human ailments in a proactive manner with corrective intervention on a large scale could be a reality. Devices acting in aiding mode and replacement mode, fabricated in biocompatible artificial materials or materials that closely replicate natural materials, should be available as tools for health care.

Ultimately, nature's way of creation and information processing, that is from molecular level and up, encoded and massively parallel, is being increasingly probed with the intention of replicating it in the area of information processing. This field already goes by the name "biomimetics". Initial efforts are obviously limited to laboratory experiments where cells are grown and manipulated. Cell interaction with various materials and known forces are being investigated—at levels which will soon approach molecular dimensions—to arm the scientists with the knowledge and skills to establish cell cultivation depots. A question for which answers are being sought is the way in which neurons respond to morphological features of their surrounding and the electrical activity that is present.

In our quest to explore devices with ever-shrinking dimensions and limitation in the tools that are brought to bear, efforts—although at the embryonic stage at the moment—are underway to learn from nature's methods or at least utilize what nature has to offer. One such example is the use of DNA strands with engineered modification as one-dimensional wires