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Vinod Kumar Khanna

Integrated Nanoelectronics

Nanoscale CMOS, Post-CMOS and Allied Nanotechnologies

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To my late father Shri Amarnath Khanna
for imparting me education and giving
wise counsel,
To my beloved mother Smt. Pushpa
Khanna, for her blessings to live happily,
to keep well and excel.
To my daughter Aloka whose endeavors
are good and wonderful,
Making the family flamboyant and cheerful,
To my wife Amita for backing me up
audaciously with grin
and standing by me through thick and thin
Rain or sunshine,
Tempestuous weather or fine!

Preface

Almost since their inception, integrated circuits have been synonymous with NMOS and CMOS technologies; the bipolar ICs reigned for some period. The primeval and perennial CMOS has borne the brunt and onslaught of brutal miniaturization, and has been stubbornly holding on to maintain its supremacy. It has also received ample support from its nanotechnological cousins like nanophotonics, nanomechanics, nanobiotechnology and spintronics. Receiving this support, it has blossomed into beautiful flowers and fruits of “CMOS applications”, which have cast a tremendous influence on human life at large. The CMOS IC tree has also burgeoned into relatively new areas, spreading into and embracing all spheres of our lives. Indeed, so profound and overwhelming has been the CMOS proliferation!

Over the past few decades, the researchers have also been constantly bothered by the question: What next after CMOS? So scientists have diverted their attention towards exploratory research in quest of potential CMOS alternatives. A noteworthy consequence of this progress has been that nanoelectronics no longer remains a solo silicon semiconductor technology. One must broaden thinking to include other materials such as carbon one-dimensional materials like carbon nanotubes. There are two-dimensional materials, e.g., graphene and dichalcogenides. Several polymers and biological materials like DNA are important too. Nanoelectronics is no longer the forte of physicists and electrical engineers. Biophysicists, chemists, and biologists equally partake in this field. It appears that physics, engineering, chemistry, biology, and related rivulets have all merged together into nanoelectronics to provide the solutions to unabated shrinkage of devices and circuits.

Transistor switches are not the only possible means of implementing logic operations. One must envisage other models like quantum dot cellular automata or magnetic cellular automata. Wired circuits may not be always required. Wireless field-coupled modus operandi must be foreseen. Room temperature operation should not be compulsorily followed. Superconductive nanoelectronics has its own benefits. Innovative circuit designs and system architectures must be visualized for increased energy efficiency in information processing.

In view of these developments, nanoelectronics of today is an interdisciplinary science and technology poised at the intersection and crossroads of several tributaries of knowledge. This book seeks to present an interdisciplinary perspective of nanoelectronics in contrast to hitherto followed view of looking at it merely from physics and electrical engineering angle. In this respect, it differs from existing books, which concentrate more on the electrical engineering aspects, and less on cross-disciplinary view. In line with the above thinking, the readers will find five parts of this book: (i) A part laying down the groundwork for understanding the subject matter. (ii) A part treating about MOSFET and CMOS technologies, the scaling issues, problems faced in short-channel devices and their remedies, the structural innovations in the form of partially- and fully-depleted SOI MOSFETs, FINFETs and multigate architectures. (iii) A part on sister nanotechnogies of CMOS, viz., those from optical, magnetic, mechanical and biological families. (iv) A part on post-CMOS futuristic technologies like resonant tunneling diodes, tunnel FETs, single-electron transistors, one-dimensional material platforms, e.g., silicon nanowires and carbon nanotubes, two-dimensional materials, like graphene and transition metal dichalcogenides, quantum dot cellular automata, magnetic cellular quantum automata, rapid single flux quantum devices, and finally molecular electronics. (v) A concluding part on nanofabrication techniques and diagnostic instrumentation.

The book is targeted to an assorted audience, which includes but is not limited to graduate students of electrical and electronics engineering, physics, chemistry, nanotechnology, semiconductor fabrication technology, and related courses. Professional engineers and scientists engaged in this frontier field will also be immensely benefitted.

Pilani, India Vinod Kumar Khanna

Acknowledgments

It is a pleasure to express my unfathomable gratitude and earnest appreciation to all those who have explicitly or implicitly helped me in this project. *Prima facie*. I am indebted to Almighty God. I thank God for granting me health, wellbeing, vigor, energy, and patience.

> Neither any words nor any actions are adequate to express thankfulness,
> All words fall short and all efforts seem too less!

Without God's grace, it is impossible to do any work, big or small.

I gratefully acknowledge the authors of all books, journal articles and web pages, which have been consulted in this compilation. Many of these esteemed names appear in the references list at the end of each chapter. If any name is missed, it may please be forgiven as an inadvertent omission.

I wish to thank the Director, CSIR-CEERI, Pilani, as well as scientists and colleagues at CSIR-CEERI for encouragement, guidance and support.

I am thankful to my acquisitions editor and project co-coordinator at Springer for offering me this opportunity, and for their kind cooperation and ardent efforts rendering possible timely completion of the project.

The acknowledgments section will remain lacking and unfinished if I do not record my gratefulness to my family. They provided me the valuable time and environment during holidays and evenings for writing this book.

Thanks to everyone from the bottom of my heart!

Pilani, India — Vinod Kumar Khanna

About This Book

Integrated Nanoelectronics presents an interdisciplinary perspective of nanoelectronics, unifying the aspects of contemporary CMOS and ancillary nanotechnologies like nanophotonics, NEMS, biotechnology, and spintronics with futuristic "beyond CMOS" technologies, which are likely to take the baton forward after CMOS has exhausted its full potentiality of miniaturization gimmicks. From the present scenario of research trends, it is obvious that fundamental innovations in device and circuit designs and architectures together with introduction of novel paradigms in information representation, storage, transmission, processing, and computation are envisioned to prompt vital breakthroughs. Nanoelectronics of next decade and further is more likely to depend on inputs from diverse fields including physics, chemistry, and biology, and their cross-fertilization. The multidisciplinary growth of nanoelectronics is therefore stressed all throughout the text.

Commencing from the preliminary background material laying down the foundation for easy understanding, the progress in mainstream CMOS nanoelectronics is sketched out. Several supportive nanotechnologies are carrying the burden shoulder-to-shoulder with CMOS. The role played by these nanotechnologies in sensors, actuators, and other fields is enumerated. The steady march of CMOS and its companion technologies over a long triumphant period is getting bogged down by physical and practical limitations. In preparation for the future, several new avenues are explored in the form of resonant tunneling diodes, tunnel FETs, single-electron transistors, quantum dot cellular automata, magnetic quantum cellular automata, rapid single flux quantum logic, and molecular electronics. Readers will also find chapters on advanced nanofabrication and nanocharacterization facilities, which constitute the heart and soul of a nanoelectronics laboratory.

The book presents a lucid description of vast variety of topics reinforced by an elegant mathematical treatment. Students, engineers, and scientists alike will be immensely benefited from the comprehensive coverage of state-of-the-art nanotechnologies and their future trends in this explosively growing field.

Contents

About the Author

Vinod Kumar Khanna born on November 25, 1952 at Lucknow, Uttar Pradesh, India, is an Emeritus Scientist at CSIR-Central Electronics Engineering Research Institute, Pilani, Rajasthan, India, and Emeritus Professor, AcSIR (Academy of Scientific and Innovative Research), India. He is former Chief Scientist and Head, MEMS and Microsensors Group, CSIR-CEERI, Pilani, and Professor, AcSIR. During his service tenure of more than 34 years at CSIR-CEERI, starting from April 1980, he worked on various research and development projects on power semiconductors devices (high-current and high-voltage rectifier, high-voltage TV deflection transistor, power Darlington transistor, fast switching thyristor, power DMOSFET and IGBT), PIN diode neutron dosimeter and PMOSFET gamma ray dosimeter, ion-sensitive field-effect transistor (ISFET), microheater-embedded gas sensor, capacitive MEMS ultrasonic transducer (CMUT), and other MEMS devices. His research interests were micro- and nanosensors, and power semiconductor devices. From 1977 to 1979, he was Research Assistant in the Physics Department, Lucknow University.

Dr. Khanna's deputations abroad include Technische Universität Darmstadt, Germany, 1999; Kurt-Schwabe-Institut für Mess- und Sensortechnik e.V., Meinsberg, Germany, 2008; and Institute of Chemical Physics, Novosibirsk, Russia, 2009. He also participated and presented research papers at IEEE-IAS Annual Meeting, Denver, Colorado, USA, 1986.

Dr. Khanna received his M.Sc. degree in Physics with specialization in Electronics from the University of Lucknow in 1975, and Ph.D. degree in Physics from Kurukshetra University, Kurukshetra, Haryana, in 1988 for his work on thin-film aluminum oxide humidity sensor. A fellow of the Institution of Electronics and Telecommunication Engineers (IETE), India, he is a life member of Indian Physics Association (IPA), Semiconductor Society (SSI), India and Indo-French Technical Association.

Dr. Khanna has published nine books, six chapters in edited books, and 181 research papers in national/international journals and conference proceedings; he holds two US and two Indian patents.

Abbreviations, Acronyms, Chemical Symbols and Mathematical Notation

$(H_2C_2S_2C)_2$	Tetrathiafulvalene
$(NC)_2CC_6H_4C(CN)_2$	Tetracyanoquinodimethane
$(NH_4)_2MoS_4$	Ammonium tetrathiomolybdate
$(NH_4)_2WS_4$	Ammonium Tetrathiotungstate
°C	Degree centigrade
1-D, 2-D, 3-D	One-, two-, and three-dimensional
1T-MoS_2	Tetragonal molybdenum sulfide
2H-MoS_2	Hexagonal molydenum sulfide
A	Ampere
AC	Alternating current
AchE	Acetylcholinesterase
AD FINFET	Asymmetric drain–source doped FINFET
ADSE FINFET	Asymmetric drain-spacer-extended FINFET
AES	Auger electron microscopy
AFM	Atomic force microscope
Ag	Argentum (Silver)
Al_2O_3	Aluminum oxide
AlAs	Aluminum arsenide
ALD	Atomic layer deposition
AlF_3	Aluminum fluoride
AlGaAs	Aluminum gallium arsenide
AlGaN	Aluminum gallium nitride
AlN	Aluminum nitride
AMR	Anisotropic magnetoresistance
APS	Aminopropylsilatrane
APTES	(3-Aminopropyl) triethoxysilane
Ar	Argon
ASG	Asymmetric gate-workfunction FINFET
ATP	Adenosine Triphosphate
Au	Aurum (Gold)

AuNP	Gold nanoparticle
BBF	Blown bubble film (method)
BCP	Block copolymer
BESOI	Bond and Etch-Back SOI
$BiFeO_3$	Bismuth ferrite
BJT	Bipolar junction transistor
BN	Boron nitride
BOX	Buried oxide
BRET	Bioluminescence Resonance Energy Transfer
C	Carbon, Coulomb
$C_{10}H_8S_2$	Dithienylethene
$C_{12}H_{26}S$	Dodecanethiol
$C_{18}H_{35}NH_2$	Oleylamine
C_2H_2	Acetylene
C_2H_4	Ethylene
C_2H_6O	Ethanol
$C_2H_6O_2$	Ethylene glycol
$C_4H_5N_3O$	Cytosine
$C_5H_{10}O_4$	Deoxyribose
$C_5H_{10}O_5$	Ribose
$C_5H_5N_5$	Adenine
$C_5H_5N_5O$	Guanine
$C_5H_6N_2O_2$	Thymine
C_6H_6	Benzene
CAD	Computer-aided design
CaDPA	Calcium dipicolinate
CCD	Charge control device
CdSe	Cadmium selenide
CdTe	Cadmium telluride
CE	Chemical enhancement
CH_2	Methylene group
$-CH_2CH_3$	Ethyl group
$-CH_3$	Methyl group
CH_3SH	Methyl mercaptan, Methanethiol
CH_4	Methane
CHE	Channel hot electron
–CHO	Carbonyl group
CIP	Current-in-plane
CLIO	Cross-linked iron oxide
cm	Centimeter
CMC	Ceramic matrix composite
CMCS	*O*-carboxymethyl chitosan
CMOS	Complementary metal–oxide–semiconductor
CMP	Chemical mechanical polishing
–CN	Cyanide group

CNT	Carbon nanotube
CO	Carbon monoxide
Co	Cobalt
$CoFe_2O_4$	Cobalt ferrite
Con A	Concanavalin A
COOH	Carboxyl group
CPP	Current-perpendicular-to-plane
Cr	Chromium
CRET	Chemiluminescence resonance energy transfer
Cu	Cuprum (Copper)
CVD	Chemical vapor deposition
DAHC	Drain avalanche hot carrier
dB	Decibel
DBQW	Double barrier quantum well structure
DC	Direct current
DIBL	Drain-induced barrier lowering
DLS	Dynamic light scattering
DMR	Diagnostic magnetic resonance
DNA	Deoxyribonucleic acid
DRAM	Dynamic random-access memory
DSA	Directed self-assembly
DTT	Dithiothreitol
DUV	Deep ultra violet
E-beam	Electron beam
EBL	Electron beam lithography
EC	European Commission
E-DNA	Ethylated DNA
EDTA	Ethylenediaminetetraacetic acid ($C_{10}H_{16}N_2O_8$)
EDX	Energy dispersive X-ray analysis
EME	Electromagnetic enhancement
EOT	Equivalent oxide thickness
EPL	Electron projection lithography
ESCA	Electron spectroscopy for chemical analysis
EUV	Extreme UV lithography
eV	Electron volt
F	Farad
FD	Fully depleted
Fe	Ferrum (Iron)
FESEM	Field-emission scanning electron microscope
FET	Field-effect transistor
FIB-SEM	Focused ion beam scanning electron microscope
FINFET	Fin field-effect transistor
fM	Femtomolar
FRET	Förster (fluorescence) resonance energy transfer
FT-IR	Fourier transform infrared spectroscopy

FUSI	Fully silicided (polysilicon gates)
g	Gram
GaAs	Gallium arsenide
GaN	Gallium nitride
GaP	Gallium phosphide
Gbps	Gigabit per second
GBps	Gigabyte per second
GCE	Glassy carbon electrode
Ge	Germanium
GHz	Gigahertz
G-line	436 nm
GMR	Giant magnetoresistance
GNP	Gold nanoparticle
GNR	Graphene nanoribbon
GOD	Glucose oxidase
H	Hydrogen
H_2O_2	Hydrogen peroxide
h-BN	Hexagonal boron nitride
HBT	Heterojunction bipolar transistor
HDD	Hard disk drive
He	Helium
$Hf[NEt_2]_4$	Tetrakis(diethylamido)hafnium
HfO_2	Hafnium oxide
HOMO	Highest occupied molecular orbital
HOPG	Highly oriented pyrolytic graphite
HRP	Horseradish peroxidase
Hz	Hertz
I	Iodine, Intrinsic
IBM	International Business Machines Corporation
IC	Integrated circuit
IG FINFET	Isolated gate FINFET
IgG	Immunoglobulin G
I-line	365 nm
InGaAs	Indium gallium arsenide
InP	Indium phosphide
IR	Infrared
Ir	Iridium
ISO	International Standards Organization
J	Joule
JJ	Josephson junction
JTL	Josephson transmission line
K	Kelvin
kΩ	Kilo ohm
keV	Kilo electron volt
LA	Laser ablation

La_2O_3	Lanthanum oxide
LaB_6	Lanthanum hexaboride
LB	Langmuir–Blodgett
LbL	Layer-by-layer
LDD	Lightly doped drain
LDV	Laser Doppler vibrometer
LPP	Laser-produced plasma
LSPR	Localized surface plasmon resonance
LUMO	Lowest unoccupied molecular orbital
M	An atom of transition metal in the formula MX_2
m	Meter, mass
mA	Milliampere
MBE	Molecular beam epitaxy
MBs	Molecular beacons
MCBJ	Mechanically controlled break junction
MEMS	Microelectroechanical systems
meV	Millielectron volt
Mg	Magnesium
mg	Milligram
MG/HK	Metal gate/High κ (gate stack)
MgF_2	Magnesium fluoride
MgO	Magnesium oxide
MIPG	Metal inserted polysilicon gate
mm	Millimeter
mM	Millimolar
Mn	Manganese
Mo	Molybdenum
MOCVD	Metal-organic chemical vapor deposition
MODFET	Modulation-doped field-effect transistor
MOM	Methoxymethyl (group)
MoO_3	Molybdenum trioxide
MoS_2	Molybdenum disulfide
MOSFET	Metal–oxide–semiconductor field-effect transistor
MPa	Megapascal
MQCA	Magnetic quantum cellular automata
MR	Magnetoresistance
MRAM	Magnetic random-access memory
MRI	Magnetic resonance imaging
MRS	Magnetic resonance switch
MTJ	Magnetic tunnel junction
MV	Megavolt
mV	Millivolt
MWCNT	Multiwalled carbon nanotube
N	Nitrogen, Newton
nA	Nanoampere