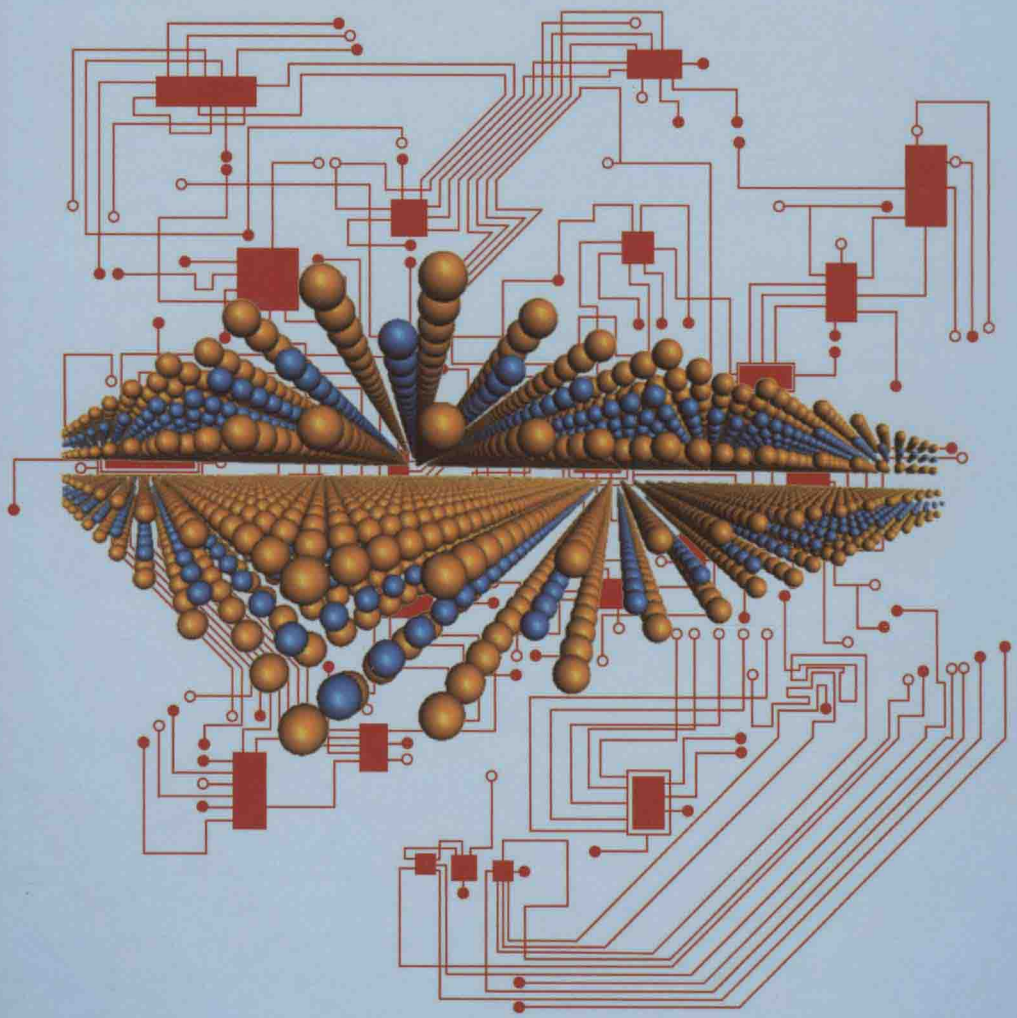
EMERGING NANOELECTRONIC DEVICES

Edited by

AN CHEN • JAMES HUTCHBY • VICTOR ZHIRNOV • GEORGE BOURIANOFF



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An Chen
GLOBALFOUNDRIES, USA

James Hutchby
Semiconductor Research Corporation, USA

Victor Zhirnov
Semiconductor Research Corporation, USA

George Bourianoff
Intel Corporation, USA

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To
Linda Wilson

Preface

Continued dimensional and functional[1] scaling of CMOS[2] integrated circuit technology is driving information processing[3] systems into a broadening spectrum of new applications. Many of these applications are enabled by performance gains and/or increased complexity realized by scaling. Because dimensional scaling of CMOS eventually will approach fundamental limits, several new alternative information processing devices and microarchitectures for existing or new functions are being explored to sustain the historical integrated circuit scaling cadence and reduction of cost/function in future decades. This is driving interest in new devices for information processing and memory, new technologies for heterogeneous integration of multiple functions (a.k.a. "More than Moore"), and new paradigms for systems architecture.

This book is based on the ITRS Emerging Research Device (ERD) International Technical Work Group's efforts over more than ten years to survey, research, and assess many of these new devices. As such, it provides an ITRS perspective on emerging research nanodevice technologies and serves as a bridge between CMOS and the realm of nanoelectronics beyond the end of CMOS dimensional and equivalent functional scaling. (Material challenges related to emerging research devices are addressed in a complementary ITRS chapter entitled *Emerging Research Materials*.)

An overarching goal of the ERD is to identify, assess, and catalog viable new information processing devices and systems architectures for their long-range potential and technological maturity, and to identify the scientific/technological challenges gating their acceptance by the semiconductor industry as having acceptable risk for further development. The intent is to provide an objective, informative resource for the constituent nanoelectronics communities pursuing: (1) research, (2) tool development, (3) funding support, and (4) investment, each directed to developing a new information processing technology. These communities include universities, research institutes, industrial research laboratories, tool suppliers, research funding agencies, and the semiconductor industry.

[1] *Functional Scaling*: Suppose that a system has been realized to execute a specific function in a given, currently available, technology. We say that system has been functionally scaled if the system is realized in an alternate technology such that it performs the identical function as the original system and offers improvements in at least one of size, power, speed, or cost, and does not degrade in any of the other metrics.

[2] Martin Hilbert and Priscila López, 2001, "The World's Technological Capacity to Store, Communicate, and Compute Information", *Science*, 332(6025), 60–65.

[3] Information processing refers to the input, transmission, storage, manipulation or processing, and output of data. The scope of this book is restricted to data or information manipulation, transmission, and storage.

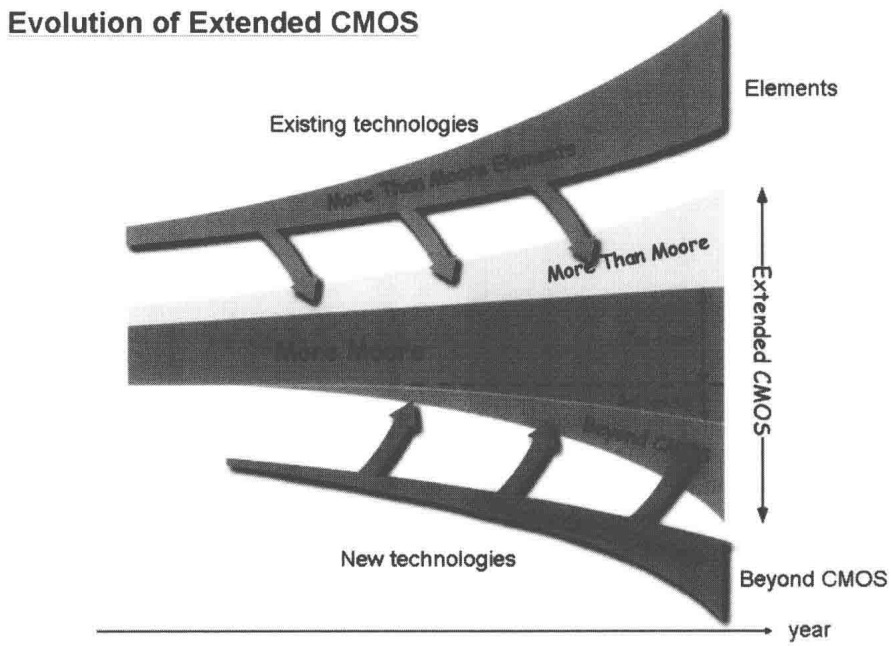

Figure P.1 Relationship between More Moore, More than Moore, and Beyond CMOS (Source: ERD, Japan)

This goal is accomplished by addressing two technology-defining domains: (1) extending the functionality of the CMOS platform via heterogeneous integration of new technologies, and (2) stimulating the invention of a new information processing paradigm. The relationship between these domains is schematically illustrated in Figure P.1. The expansion of the CMOS platform by conventional dimensional and functional scaling is often called "More Moore". The CMOS platform can be further extended by the "More than Moore" approach which is a relatively new subject. On the other hand, new information processing devices and architectures are often called "Beyond CMOS" technologies and are the main subjects addressed in this book. The heterogeneous integration of "Beyond CMOS" and "More than Moore" onto the "More Moore" platform will extend CMOS functionality to form the ultimate "Extended CMOS".

The book is partitioned into five sections: (1) Introduction, including a fundamental description of the physics of some nanodevices, (2) nanoelectronic memory devices, (3) nanoelectronic logic information processing devices, (4) concepts for emerging architectures, and (5) summary, conclusions, and outlook for nanoelectronic devices. Some detail is provided for each entry regarding operation principles, advantages, technical challenges, maturity, and its current and projected performance. Also included is a device and architectural focus combining emerging research devices offering specialized, unique functions as heterogeneous core processors integrated with a CMOS platform technology. This represents the nearer-term focus of this work, with the longer-term focus remaining on the discovery of an alternate information processing technology to supplement and to eventually replace digital CMOS.

List of Contributors

Ethan C. Ahn, Department of Electrical Engineering, Stanford University, USA

Masakazu Aono, WPI Center for Materials Nanoarchitectonics, National Institute for Materials Science, Japan

Tetsuya Asai, Graduate School of Information Science and Technology, Hokkaido University, Japan

Behtash Behin-Aein, GLOBALFOUNDRIES Inc., USA

Benjamin F. Bory, Eindhoven University of Technology, The Netherlands

George Bourianoff, Components Research Group, Intel Corporation, USA

Geoffrey W. Burr, IBM, USA

An Chen, GLOBALFOUNDRIES Inc., USA

Donald M. Chiarulli, Department of Electrical and Computer Engineering, University of Pittsburgh, USA

György Csaba, University of Notre Dame, USA

Shamik Das, Nanosystems Group, The MITRE Corporation, USA

Denver H. Dash, Intel Science and Technology Center, USA

Supriyo Datta, Purdue University, USA

Vinh Quang Diep, Purdue University, USA

S. Burc Eryilmaz, Department of Electrical Engineering, Stanford University, USA

Yan Fang, Department of Electrical and Computer Engineering, University of Pittsburgh, USA

Scott Fong, Department of Electrical Engineering, Stanford University, USA

Aaron D. Franklin, Department of Electrical and Computer Engineering and Department of Chemistry, Duke University, USA

Paul Franzon, North Carolina State University, USA

Tsuyoshi Hasegawa, WPI Center for Materials Nanoarchitectonics, National Institute for Materials Science, Japan

Toshiro Hiramoto, Institute of Industrial Science, The University of Tokyo, Japan

James Hutchby, Semiconductor Research Corporation, USA

Louis Hutin, Department of Electrical Engineering and Computer Sciences, University of California, USA

Adrian M. Ionescu, Ecole Polytechnique Fédérale de Lausanne, Switzerland

Mahdi Jamali, University of Minnesota, USA

Rakesh Jeyasingh, Department of Electrical Engineering, Stanford University, USA

Alexander Khitun, Material Science and Engineering, University of California, USA

Angeline Klemm, University of Minnesota, USA

Takhee Lee, Department of Physics, Seoul National University, Korea

Steven P. Levitan, Department of Electrical and Computer Engineering, University of Pittsburgh, USA

Eike Linn, Institute of Electronic Materials II, RWTH Aachen University, Germany

Tsu-Jae King Liu, Department of Electrical Engineering and Computer Sciences, University of California, USA

Matthew J. Marinella, Sandia National Laboratories, USA

Hao Meng, Data Storage Institute, Singapore

Stephan Menzel, Peter Grünberg Institut (PGI-7), Forschungszentrum Jülich, Germany

Stefan C.J. Meskers, Eindhoven University of Technology, The Netherlands

Michael T. Niemier, University of Notre Dame, USA

Ferdinand Peper, Center for Information and Neural Networks, National Institute of Information and Communications Technology, USA

Wolfgang Porod, University of Notre Dame, USA

Mark A. Reed, Departments of Electrical Engineering and Applied Physics, Yale University, USA

Frank Schwierz, Technical University of Ilmenau, Germany

Hyunwook Song, Department of Applied Physics, Kyung Hee University, Korea

Narayan Srinivasa, Center for Neural and Emergent Systems, HRL Laboratories LLC, USA

Ken Takeuchi, Chuo University, Japan

Jian-Ping Wang, University of Minnesota, USA

Rainer Waser, Institute of Electronic Materials II, RWTH Aachen University, Germany; Peter Grünberg Institut (PGI-7), Forschungszentrum Jülich, Germany

H.-S. Philip Wong, Department of Electrical Engineering, Stanford University, USA

Victor V. Zhirnov, Semiconductor Research Corporation, USA

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Acronyms

1D1R	1-Diode-1-resistor
1S1R	1-Selector-1-resistor
1T	One transistor
1T1C	1-Transistor-1-capacitor
1T1R	1-Transistor-1-resistor
2DEG	Two-dimensional electron gas
3D	Three dimensional
AD	Analog digital
AF	Anti-ferromagnetic
AIST	Silver (Ag) Indium (In) Antimony (Sb) Tellurium (Te)
ALD	Atomic layer deposition
AM	Associative memory
ASIC	Application specific integrated circuit
ASL	All-spin logic
BARITT diode	Barrier-injection transit-time diode
BBE	Brain, body, environment based interactions
BBL	Buried bit line
BDA	1,4-Benzenediamine
BDC60	Bis(fullero[c]pyrolidin-1y1)benzene
BDT	1,4-Benzenedithiol
BE	Bottom electrode
BEC	Bottom electrode contact
BEOL	Back end of line
BFO	Bismuth ferrite (BiFeO3)
BiSFET	Bilayer pseudo-spin field-effect transistor
BIST	Built-in self-test
BJT	Bipolar junction transistor
BL	Bit line
BLG	Bilayer graphene
BN	Beyond Neumann
CA	Cellular automata
CAM	Contend addressable memory

CBL	Cantilever bit line
CBRAM	Conductive-bridge random access memory
CDMA	Code division multiple access
CMIS	Current-induced magnetization switching
CMOS	Complementary metal oxide semiconductor
CNT	Carbon nanotube
CNTFET	Carbon nanotube field-effect transistor
CO	Carbon monoxide
CoFeB	Cobalt iron boron
CoPt	Cobalt platinum
CP-AFM	Conducting probe–atomic force microscopy
CPP	Current perpendicular to plane
CPU	Central processing unit
CRS	Complementary resistive switch
CTAFM	Conductive-tip atomic force microscopy
D	Density of states
DC	Direct contact
DC8 to DC12	Eight to 12 carbon atoms in alkanedithiols
dCNT	Carbon nanotube diameter
DFT	Density functional theory
DIBL	Drain induced barrier lowering
DMRG method	Density matrix renormalization group method
DNA	Deoxyribonucleic acid
DoM	Degree of match
DOS	Density of states
DRAM	Dynamic random access memory
DVD	Digital versatile disc
e	Elementary charge of an electron
EBIC	Electron beam induced current
EBJs	Electromigrated break junctions
EEPROM	Electrically erasable programmable read only memory
Eg	Energy bandgap
EM	Electromechanical
EMB	Electrochemical metallization bridge
EOT	Equivalent oxide thickness
ERD	Emerging research devices
FD	Fully depleted
FeFET	Ferroelectric field effect transistor
Fe-NAND	Ferroelectric NAND
FeRAM	Ferroelectric random access memory
FERET	Facial recognition technology
FET	Field-effect transistor
FIB	Focused ion beam
FinFET	Multi-gate MOSFET with fin-shaped active structure

FL	Free layer
FM	Ferromagnetic
FN	Fowler–Nordheim
FOPE	Fluorinated oligomer
FPGA	Field programmable gate array
FRAM	Ferroelectric random access memory
FTJ	Ferroelectric tunnel junction
FWHM	Full width at half maximum
GAA	Gate all around
GaAs	Gallium arsenide
GMR	Giant magnetoresistive
GNM	Graphene nanomesh
GNR	Graphene nanoribbon
GQ	Quantum conductance
GSHE	Giant spin Hall effect
GST	Germanium (Ge), Antimony(Sb), Tellurium(Te)
h	Planck's constant
HAO	Hf-Al-O
HDD	Hard disk drive
HEMT	High electron mobility transistor
HF	Hydrofluoric acid
HKMG	High-k metal gate
HMAX	Hierarchical memory and X
HOMO	Highest occupied molecular orbital
HP	High performance
HRS	High resistance state
HTM	Hierarchical temporal memory
IC	Integrated circuit
ICT	Information and communication technologies
IEDM	International Electron Devices Meeting
IETS	Inelastic electron tunneling spectroscopy
I-MOS	Impact-ionization MOS
InAlAs	Indium aluminum arsenide
InAs	Indium arsenide
InGaAs	Indium gallium arsenide
iNML	In-plane nanomagnet logic
InP	Indium phosphide
InSb	Indium antimonide
I_{off}	Off current
I_{on}	On current
IOP	Input–output processor
IPCM	Interfacial phase change memory
ITRS	International Technology Roadmap for Semiconductors

KJMA	Kolmogorov, Johnson and Mehl, and Avrami
L_{ch}	Channel length
LEC	Lyric error correction
L_g	Gate length
LLG	Landau–Lifshitz–Gilbert
LRS	Low resistance state
L_{spr}	Spacer length
LtN	Less than Neumann
LUMO	Lowest unoccupied molecular orbital
m	Carrier effective mass
MC	Magneto current ratio
MCBJs	Mechanically controllable break junctions
MEMS	Micro-electro-mechanical systems
MFIS	Metal ferroelectric insulator semiconductor
MFTJ	Multiferroic tunnel junctions
MG	Multigate
mHEMT	Metamorphic HEMT
MIEC	Mixed ionic electronic conduction
MIM	Metal–insulator–metal
MIT	Metal–insulator transition
MLC	Multi level cell
MO-BF	Metal oxide–bipolar filamentary
MOS	Metal oxide semiconductor
MoS_2	Molybdenum disulfide
$MoSe_2$	Molybdenum diselenide
MOSFET	Metal oxide semiconductor field-effect transistor
MO-UF	Metal oxide–unipolar filamentary
MQCA:	Magnetic quantum-dot cellular automata
MRAM	Magnetic random access memory
M-SCM	Memory class storage class memory
MTJ	Magnetic tunnel junction
MtN	More than Neumann
Nc	Nanocrystal
NCC	Nano-current channel
ND	Notre Dame
NEMory	Memory cell based on a NEMS switch
NEMS	Nano-electro-mechanical systems
NIST:	National Institute of Standards and Technology
NML	Nanomagnet logic
nMOSFET	n-Channel MOSFET
N-T	N-Terminal relay
NV	Nonvolatile
NVM	Nonvolatile Memory
NWFET	Nanowire field-effect transistor

ODT	Au-octanedithol junction
ONO	Oxide–nitride–oxide
OOMMF	Object oriented micromagnetic framework
OPE	Oligophenyleneethynynylene
OPI	Oligophenyleneimine
OPV	Oligophenylenevinylene
OS	Operating system
OTP	One-time programmable
OTS	Ovonic threshold switch
PABA	Persistent asynchronous background activity
PC	Phase change
PCB	Phase change bridge
PCM	Phase change memory
PCRAM	Phase change random access memory
PDMS	Polydimethylsiloxane
PE	Piezoelectric
PE:	Processing element
PET	Piezoelectronic transistor
PF	Poole Frenkel
PFM	Piezoresponse force microscopy
pHEMT	Pseudomorphic HEMT
PIDS	Process integration, devices, and structures
PLA	Programmable logic array
PLL	Phase-locked loop
PM	Permanent magnet
pMA	Pars-mercaptoaniline
PMA	Perpendicular magnetic anisotropy
PMN-PT	Lead magnesium niobate – lead titanate
pMOSFET	p-Channel MOSFET
pNML:	Perpendicular nanomagnet logic
PR	Piezoresistive
PS-MOSFET	Pseudo-spin MOSFET
PZN-PT	Lead zinc niobate–lead titanate
PZT	Lead zirconate titanate
QCA	Quantum-dot cellular automata
R	Read
R6G	Rhodamine
RA	Resistance × area
RAM	Random access memories
R_c	Contact resistance
RC	Time constant of a circuit composed of resistors and capacitors
RDF	Random dopant fluctuation
ReRAM	Redox resistive random access memory
RF	Radio frequency

RIE	Reactive ion etch
RL	Reference layer
RQ	Quantum resistance
RRAM	Resistive random access memory
RTD	Resonant tunneling diode
RWL	Read word line
SAM	Self-assembled monolayer
SB	Schottky barrier
SBM	Suspended beam memory
SBT	$SrBi_2Ta_2O_9$
SCE	Short channel effect
SCLC	Space–charge limited conduction
SCM	Storage class memory
SEM	Scanning electron microscopy
SERS	Surface-enhanced Raman spectroscopy
SET	Single electron transistor
SEU	Single event upset
SFD:	Switching field distribution
SG	Suspended gate
Si	Silicon
SLL	Super lattice like
SNDM	Scanning nonlinear dielectric microscopy
SNM	Static noise margin
SoC	System on a chip
SOI	Silicon on insulator
SPDT	Single pole double-throw
SPT	Structural phase transition
SR	Structural relaxation
SR	Stochastic resonance
SRAM	Static random access memory
SS	Subthreshold swing
S-SCM	Storage class storage class memory
SSD	Solid state disk
STD	Spin torque device
STDP	Spike timing dependent plasticity
STM	Scanning tunneling microscopy
STM-BJ	Scanning tunnel microscope controlled break junction
STMG	Spin torque majority logic gate
STNO	Spin torque nano-oscillator
STS	Scanning tunneling spectroscopy
STS	Subthreshold slope
STT	Spin transfer torque
STT-MRAM	Spin torque transfer magnetic random access memory
SWD	Spin wave devices
SWNT	Single walled carbon nanotube

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