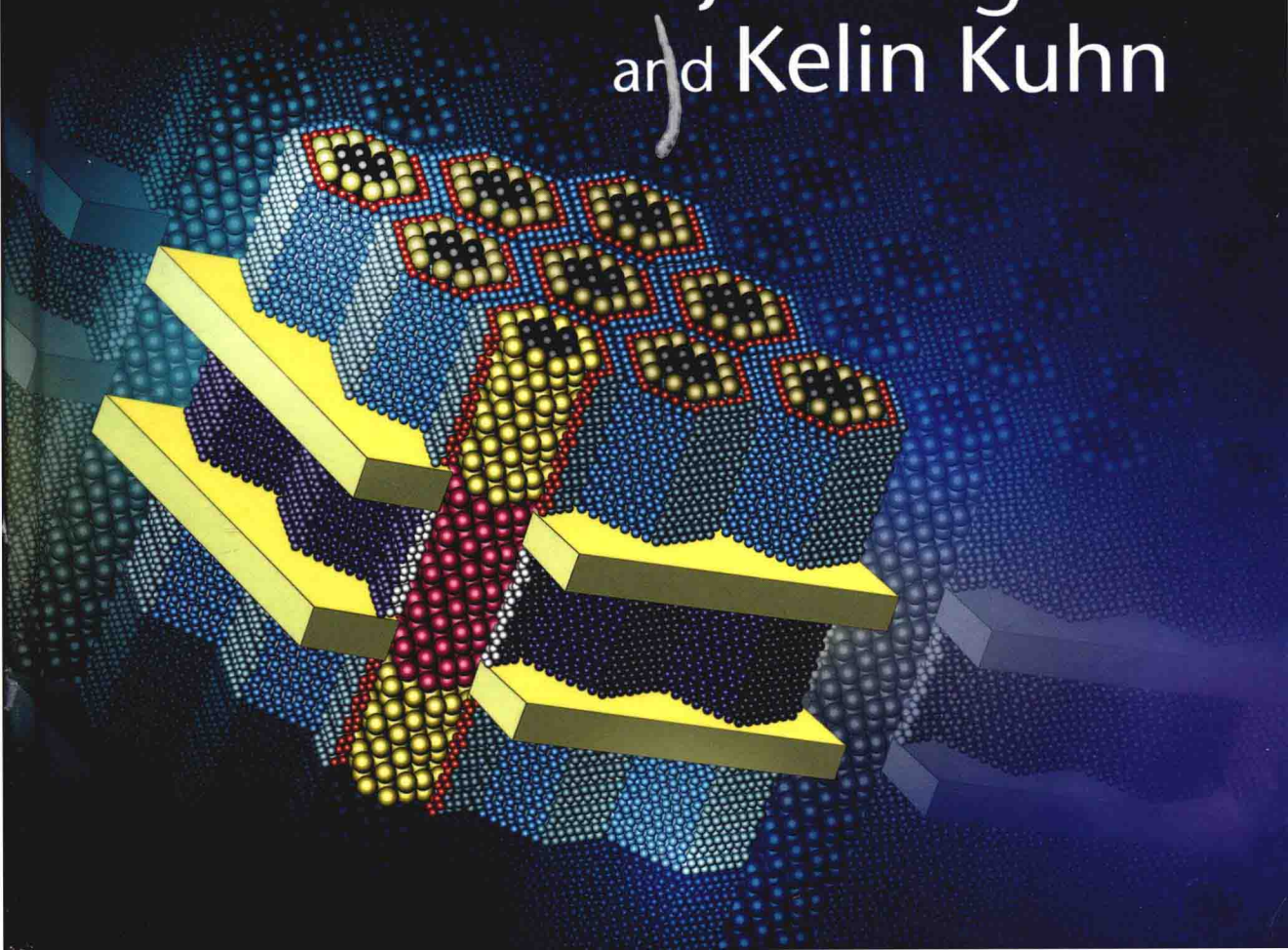


CMOS AND BEYOND

Logic Switches for Terascale
Integrated Circuits

Edited by
Tsu-Jae King Liu
and Kelin Kuhn



CMOS and Beyond

Logic Switches for Terascale Integrated Circuits

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CMOS and Beyond

Get up to speed with the future of logic switch design with this indispensable overview of the most promising successors to modern CMOS transistors.

Learn how to overcome existing design challenges using novel device concepts, presented using an in-depth, accessible, tutorial-style approach. Drawing on the expertise of leading researchers from both industry and academia, and including insightful contributions from the developers of many of these alternative logic devices, new concepts are introduced and discussed from a range of different viewpoints, covering all the necessary theoretical background and developmental context.

Covering cutting-edge developments with the potential to overcome existing limitations on transistor performance, such as tunneling field-effect transistors (TFETs), alternative charge-based devices, spin-based devices, and more exotic approaches, this is essential reading for academic researchers, professional engineers, and graduate students working with semiconductor devices and technology.

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Preface

Steady miniaturization of CMOS (complementary metal–oxide–semiconductor) transistors – the predominant type of electrical switches used in digital integrated circuit “chips” – has yielded continual improvements in the performance and cost-per-function of electronic devices over the past four decades. This relentless miniaturization has resulted in ubiquitous information technology with dramatic global impact on virtually every aspect of life in modern society.

CMOS technology is reaching a state of maturity wherein continued transistor scaling will not be as straightforward in the future as it has been in the past. This is already apparent from the slowdown in certain aspects of scaling (e.g., chip supply voltage scaling, transistor off-state leakage current scaling, and so on). Clearly, improved switch designs will be needed to sustain the growth of the electronics industry beyond the next decade. A wide variety of alternative switch designs are being discussed in the research community, many of which use operating principles dramatically different from those of conventional CMOS transistors. Unfortunately, papers published by the research community in rapidly developing fields are rarely tutorial. Thus, much of this important new information is not readily comprehensible to the mainstream electronics community.

To help address this communication gap, we approached recognized experts in the research community with requests to create tutorial essays in their area of speciality. This book organizes these essays into sections, beginning with background information on the power–performance trade-off (motivating steep sub-threshold swing devices), continuing with tunneling-based devices, alternative field effect devices, and spin-based (magnetic) devices. It closes by reviewing the challenges of interconnects for these evolving new switch designs.

The first section reviews chip design considerations and benchmarks various alternative switching devices, with particular emphasis on devices with steeper sub-threshold swing. In Chapter 1, Elad Alon introduces the concepts underlying historical transistor scaling and analyses the key trade-offs between density, power, and performance which drive modern CMOS chip designs. Circuit design techniques such as power gating and parallelism are reviewed in context of constraints for continued dimensional scaling. The energy-efficiency limit for CMOS technology due to the 60 mV/dec sub-threshold swing limitation is discussed in relation to the potential benefit of beyond-CMOS devices with steeper sub-threshold swings. In Chapters 2 and 3, Zachery A. Jacobson and Kelin Kuhn review and benchmark a broad range of alternative devices being

explored in the research community. These chapters focus on electronic (as opposed to magnetic) devices that either incorporate new materials or mechanisms for enhanced switching behaviour. Chapter 2 briefly reviews the history and operating principles of these devices, while Chapter 3 benchmarks them with respect to drive current, energy efficiency, fabrication cost, complexity, and memory cell area. In Chapter 4, Asif Islam Khan and Sayeef Salahuddin explore the idea of overcoming the 60 mV/dec sub-threshold swing limit by incorporating a ferroelectric layer within the gate stack of a CMOS transistor. They discuss both the theory and recent experiments which support the possibility of achieving CMOS transistors with negative small-signal capacitance.

The second section covers device designs which utilize quantum mechanical tunneling as the switching mechanism to achieve steeper sub-threshold swing. In Chapter 5, Sapan Agarwal and Eli Yablonovitch assess the promise of tunnel field effect transistors (TFETs) in light of the requirements for simultaneous steep sub-threshold swing, large on/off-current ratio, and high on-state conductance. The authors explore the impact of p-n junction dimensionality and discuss various design trade-offs and the advantages of lateral, vertical, and bilayer implementations. Recent experimental data is evaluated in light of the various design requirements. In Chapter 6, Alan Seabaugh, Zhengping Jiang, and Gerhard Klimeck continue the discussion on TFETs, but with a focus on III-V semiconductor material systems. Design trade-offs for homojunction versus heterojunction III-V systems and challenges for achieving high performance with p-channel TFETs are discussed, along with non-idealities of particular relevance to III-V systems (such as traps, interface roughness, and alloy disorder). In Chapter 7, Qin Zhang, Pei Zhao, Nan Ma, Grace (Huili) Xing, and Debdeep Jena further extend the TFET discussion by evaluating the potential for TFETs built with graphene and two-dimensional semiconductor materials. In-plane tunneling and inter-layer tunneling devices are reviewed, and recent experimental results are assessed in relation to theoretical understanding. In Chapter 8, Dharmendar Reddy, Leonard F. Register, and Sanjay K. Banerjee review a novel tunneling device, the bilayer pseudospin field effect transistor (BiSFET). The BiSFET relies on the possibility of room temperature excitonic (electron-hole) superfluid condensation in two dielectrically separated graphene layers. Formation of a room temperature condensate is essential for BiSFET operation, and the authors discuss the key physics and challenges of creating such a condensate. BiSFET compact models and circuit designs are also discussed and used to project performance benefits over CMOS.

The third section covers devices that employ alternative approaches to achieving steeper switching behaviour. In Chapter 9, You Zhou, Sieu D. Ha, and Shriram Ramanathan discuss the possibility of making devices from electron correlated materials, which can transition between insulator and metal phases. The authors discuss the physics of the metal-insulator transition, with particular emphasis on the vanadium dioxide (VO_2) system. Mott FET devices, solid-state VO_2 FETs and ionic liquid-gated VO_2 FETs are reviewed and circuit architectures which exploit these devices are discussed. In Chapter 10, Paul M. Solomon, Bruce G. Elmegreen, Matt Copel, Marcelo A. Kuroda, Susan Trolhier-McKinstry, Glenn J. Martyna, and Dennis M. Newns introduce piezoelectronic transistor (PET) devices. The PET is essentially a solid-state relay

in which a piezoelectric element provides the mechanical force and a piezoresistive element transduces the mechanical force to electrical switching. The basic physics of piezoelectric and piezoresistive materials are discussed, along with process integration challenges. PET dynamics, compact models, and circuit designs are also discussed and used to project performance benefits over CMOS. In Chapter 11, Rhesa Nathanael and Tsu-Jae King Liu discuss nanoscale electromechanical relays as logic switches. Relays use mechanical movement to physically short or open an electrical connection between two contacts, and have the ideal characteristics of zero off-state leakage current, abrupt sub-threshold swing, and low gate leakage. The authors review materials requirements and process integration challenges specific to nanorelays, describe a variety of relay designs that provide for more compact implementation of complex logic circuits, and discuss scaling methodologies.

The fourth section covers devices that use magnetic effects or electronic spin to carry information. These can be used to implement nanomagnetic logic (wherein small magnets are used to construct circuits), spin torque logic, or spinwave logic (wherein electron spin is the information token). In Chapter 12, György Csaba, Gary H. Bernstein, Alexei Orlov, Michael T. Niemier, X. Sharon Hu, and Wolfgang Porod discuss the possibility of making circuits out of small single-domain magnets. The switching properties of single-domain nanomagnets are introduced and various clocking schemes are discussed. A full-adder structure is benchmarked against CMOS and design issues in nanomagnetic logic are reviewed. In Chapter 13, Dmitri E. Nikonov and George I. Bourianoff introduce the possibility of making majority gate logic circuits using the spin torque effect. In these devices the combined action of spin torques from the various inputs transfers enough torque to switch the magnetization of the output. Detailed simulations of in-plane and perpendicular spin torque switching are reviewed. An adder circuit is discussed and benchmarked against CMOS. In Chapter 14, Alexander Khitun analyses the possibility of using spin waves for logic functions. A spin wave is a collective oscillation of spins in a spin lattice around the direction of magnetization. The physics of spin wave devices is introduced and experimental results discussed. Various spin wave circuits and architectures are reviewed and benchmarked against CMOS.

A critical (but frequently neglected) issue in assessment of beyond CMOS devices is the interconnect architecture. Creating a fabulous new switch is valueless if it cannot be connected to other active or passive devices! This is particularly relevant for magnetic and spin-based devices as they do not (typically) interface directly to conventional electronic devices. Thus, in Chapter 15, Shaloo Rakheja, Ahmet Ceyhan, and Azad Naeemi close this book with a comprehensive evaluation of the interconnect considerations for advanced logic devices. This includes both interconnect options for emerging charge-based device technologies and interconnect options for spin-based technologies.

Our hope is that these essays will help to bridge the gap between research on emerging devices and their practical implementation in terascale integrated circuits by the mainstream semiconductor community.

Contents

<i>Contributors</i>	page xiii
<i>Preface</i>	xv

Section I CMOS circuits and technology limits

1	Energy efficiency limits of digital circuits based on CMOS transistors	3
	Elad Alon	
1.1	Overview	3
1.2	Energy–performance trade-offs in digital circuits	4
1.3	Design techniques for energy efficiency	8
1.4	Energy limits and conclusions	11
	References	12
2	Beyond transistor scaling: alternative device structures for the terascale regime	14
	Zachery A. Jacobson and Kelin J. Kuhn	
2.1	Introduction	14
2.2	Alternative device structures	14
2.2.1	HEMT	14
2.2.2	Gallium nitride	17
2.2.3	Ferroelectric-dielectric gate stacks	20
2.2.4	Electrochemical devices	22
2.2.5	Impact ionization devices	23
2.2.6	Tunnel FET	24
2.2.7	Metal source/drain devices	27
2.2.8	Relays	29
2.3	Summary	31
	References	32
3	Benchmarking alternative device structures for the terascale regime	39
	Zachery A. Jacobson and Kelin J. Kuhn	
3.1	Introduction	39
3.2	Scaling potential of alternative device structures	39
3.2.1	High electron mobility transistors (HEMT)	39

3.2.2	Gallium nitride (GaN) transistors	39
3.2.3	Negative capacitance (Fe-gate) transistors	40
3.2.4	Electrochemical transistors	40
3.2.5	Impact ionization metal-oxide semiconductor (IMOS) transistors	41
3.2.6	Tunnel field effect transistors (TFETs)	42
3.2.7	Metal source/drain transistors	42
3.2.8	Relays	43
3.3	Scaling potential of comparison devices	44
3.3.1	Ultra-thin body (UTB) transistors	44
3.3.2	Gate-all-around (GAA) transistors	44
3.3.3	Junctionless accumulation mode (JAM) transistors	45
3.3.4	Thin-film transistors	46
3.4	Evaluation metrics	47
3.5	Benchmarking results	48
3.6	Conclusions	51
	References	51
4	Extending CMOS with negative capacitance	56
	Asif Islam Khan and Sayeef Salahuddin	
4.1	Introduction	56
4.2	Intuitive picture	57
4.2.1	Why negative capacitance?	57
4.2.2	Reduction of sub-threshold swing	58
4.2.3	How can a ferroelectric material give negative capacitance?	59
4.2.4	How can we stabilize a ferroelectric material in a state of negative capacitance?	60
4.3	Theoretical framework	61
4.3.1	Temperature dependence	63
4.4	Experimental work	65
4.5	Negative capacitance transistors	70
4.6	Concluding remarks	71
	Acknowledgments	73
	References	74
Section II Tunneling devices		
5	Designing a low-voltage, high-current tunneling transistor	79
	Sapan Agarwal and Eli Yablonovitch	
5.1	Introduction	79
5.2	Tunneling barrier thickness modulation steepness	80
5.3	Energy filtering switching mechanism	82
5.3.1	Minimum effective bandgap	83
5.4	Measuring the electronic transport band edge steepness	83

5.5	Correcting spatial inhomogeneity	86
5.6	p-n junction dimensionality	87
5.6.1	1D–1D _{end} junction	87
5.6.2	Energy dependent tunneling probability	90
5.6.3	3D–3D bulk junction	92
5.6.4	2D–2D _{edge} junction	92
5.6.5	0D–1D junction	93
5.6.6	2D–3D junction	94
5.6.7	1D–2D junction	95
5.6.8	0D–0D junction	95
5.6.9	2D–2D _{face} junction	97
5.6.10	1D–1D _{edge} junction	98
5.6.11	Trade-off between current, device size, and level broadening	98
5.6.12	Comparing the different dimensionalities	100
5.7	Building a full tunneling field effect transistor	101
5.7.1	Minimum voltage required	102
5.7.2	Sub-threshold swing voltage	104
5.7.3	On-state conductance	106
5.8	Maximizing the gate efficiency	107
5.8.1	Lateral TFET gate efficiency	107
5.8.2	Vertical TFET gate efficiency	109
5.8.3	Bilayer TFET gate efficiency	110
5.9	Other design issues to avoid	112
5.10	Conclusions	113
	Acknowledgment	113
	References	113

6 Tunnel transistors 117

Alan Seabaugh, Zhengping Jiang, and Gerhard Klimeck

6.1	Introduction	117
6.1.1	Need for low-voltage and sub-threshold swing	117
6.1.2	Scope	118
6.2	Tunnel FET	119
6.2.1	Physical principles	119
6.2.2	Kane–Sze on-current	119
6.3	Materials and doping trade-offs	121
6.3.1	Homojunction on-current vs. material	121
6.3.2	Optimum TFET bandgap	122
6.3.3	Doping	123
6.3.4	Heterojunctions – broken-gap benefit	125
6.4	Geometrical considerations and gate electrostatics	126
6.4.1	Tunnel junction perpendicular to the gate	127
6.4.2	Tunnel junction parallel to the gate	128
6.4.3	p-TFET	130

6.5	Non-idealities	131
6.5.1	Traps	131
6.5.2	Band tails/phonons	132
6.5.3	Interface roughness	132
6.5.4	Alloy disorder	134
6.5.5	Variability	135
6.6	Experimental results	135
6.7	Conclusions	137
	Acknowledgments	137
	References	138
7	Graphene and 2D crystal tunnel transistors	144
	Qin Zhang, Pei Zhao, Nan Ma, Grace (Huili) Xing, and Debdeep Jena	
7.1	What is a low-power switch?	144
7.2	Brief review of 2D crystal materials and devices	145
7.3	Carbon nanotubes and graphene nanoribbons	146
7.3.1	First demonstration of less than 60 mV/dec sub-threshold swing in TFETs with carbon nanotubes	146
7.3.2	Zener tunneling in carbon nanotubes and graphene nanoribbons	146
7.3.3	TFET device structure and semi-classical modeling	148
7.3.4	Geometry and doping dependence, optimization, and benchmarks	150
7.3.5	Non-ideal effects	154
7.4	Atomically thin body transistors	155
7.4.1	In-plane tunneling transport in 2D crystals	156
7.4.2	In-plane 2D crystal TFETs	159
7.5	Interlayer tunneling transistors	162
7.5.1	Interlayer tunneling between graphene layers	163
7.5.2	Symmetric tunneling field effect transistor (SymFET)	163
7.5.3	Bilayer pseudospin FETs (BiSFETs)	166
7.5.4	Experimental progress of interlayer tunneling transistors	166
7.5.5	Challenges	170
7.6	Internal charge and voltage gain steep devices	171
7.7	Conclusions	171
	References	172
8	Bilayer pseudospin field effect transistor	175
	Dharmendar Reddy, Leonard F. Register, and Sanjay K. Bannerjee	
8.1	Introduction	175
8.2	Overview	176
8.2.1	Condensate formation and low-voltage NDR	176
8.2.2	Device layout and compact modeling	178
8.2.3	BiSFET compatible circuits and circuit simulation results	180
8.2.4	BiSFET technology	181

8.3	Essential physics	182
8.3.1	Condensate formation in bilayer graphene	182
8.3.2	Low-voltage NDR	187
8.4	BiSFET design and compact modeling	191
8.4.1	BiSFET (and BiS junction) design	191
8.4.2	Compact circuit models	194
8.5	BiSFET logic circuits and simulation results	197
8.5.1	BiSFETs logic circuit basics: how to use and how not to use BiSFETs	197
8.5.2	Circuit simulation results	199
8.6	Technology	202
8.7	Conclusions	204
	Acknowledgments	205
	References	205

Section III Alternative field effect devices

9	Computation and learning with metal–insulator transitions and emergent phases in correlated oxides	209
	You Zhou, Sieu D. Ha, and Shriram Ramanathan	
9.1	Overview	209
9.1.1	Introduction	209
9.1.2	Outline of chapter	210
9.2	Metal–insulator transition in vanadium dioxide	211
9.2.1	Electronic and structural transition	211
9.2.2	Proposed mechanisms of the phase transition	213
9.3	Field effect devices using phase transitions	217
9.3.1	Mott FET: theory and challenges	217
9.3.2	Solid-state VO ₂ -based FETs	220
9.3.3	Ionic liquid-gated VO ₂ FETs	222
9.4	Two-terminal devices utilizing phase transitions	224
9.4.1	Threshold switches, resistive memory, and neural computing	224
9.5	Neural circuits	229
9.6	Conclusions	231
	References	231
10	The piezoelectronic transistor	236
	Paul M. Solomon, Bruce G. Elmegreen, Matt Copel, Marcelo A. Kuroda, Susan Trolier-McKinstry, Glenn J. Martyna, and Dennis M. Newns	
10.1	Introduction	236
10.2	How it works	238
10.3	Physics of PET materials	240
10.3.1	Polarization rotation in relaxor-based piezoelectric single crystals	240

10.3.2	4f \rightarrow 5d electronic promotion under pressure in rare earth chalcogenide piezoresistors	242
10.3.3	Equivalent sub-threshold slope	243
10.4	PET dynamics	243
10.4.1	Electromechanical (Tiersten) equations	243
10.4.2	Simulation of logic circuits	247
10.4.3	Electromechanical lumped element circuit model for PET	247
10.4.4	Mechanical and electrical parasitics	251
10.5	Materials and device fabrication	252
10.5.1	SmSe	252
10.5.2	PMT-PT	255
10.5.3	PET fabrication – progress and issues	256
10.6	Performance estimation	257
10.7	Discussion	259
	Acknowledgments	260
	References	260
11	Mechanical switches	263
	Rhesa Nathanael and Tsu-Jae King Liu	
11.1	Introduction	263
11.2	Relay structure and operation	264
11.2.1	Electrostatically actuated relays	264
11.2.2	Relay designs	267
11.3	Relay process technology	270
11.3.1	Materials selection and process integration challenges	270
11.3.2	Relay process flow	277
11.4	Relay design optimization for digital logic	278
11.4.1	Design for improved electrostatics	278
11.4.2	Design for highly compact circuits	281
11.4.3	Design for low-voltage operation	283
11.5	Relay combinational logic circuits	286
11.5.1	Complementary relay inverter circuit	286
11.5.2	CMOS-like circuit design	287
11.5.3	Multi-input/multi-output design	289
11.6	Relay scaling perspective	292
	References	294
Section IV Spin-based devices		
12	Nanomagnetic logic: from magnetic ordering to magnetic computing	301
	György Csaba, Gary H. Bernstein, Alexei Orlov, Michael T. Niemier, X. Sharon Hu, and Wolfgang Porod	
12.1	Introduction and motivation	301
12.1.1	Magnetic computing defined	301