

# Fundamentals of III-V Semiconductor MOSFETs

Serge Oktyabrsky • Peide D. Ye  
Editors

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Springer

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# Preface

Is it true that III-V semiconductor materials are back in play for mainstream digital ICs? Or it is just another round of interest to other-than-silicon materials when Si CMOS technology is approaching just another “fundamental limit”. There is no simple answer. Moreover, the answer depends not only on physics, materials and technologies, but on economics, demand from other industries, etc. Anyway, we would like the reader to answer these questions on his/her own. The book will help by presenting the fundamentals and current status of research on III-V compound semiconductor metal-oxide-semiconductor field-effect transistors (MOSFETs). We believe it is just the right time to summarize results and provide guidelines for the future efforts because of the following recent developments in digital electronics:

- After almost 50 years of research, it is finally clear that there are technologies to make better-than-silicon MOSFETs. Although the efforts were not sustained during this long time period with ups and downs, this area is now very active with yet growing interest of researches and engineers in electronic industry and academia. The number of papers published recently on III-V MOSFETs are way higher than at any given time in the past.
- Silicon oxide is out of play in mainstream Si CMOS. That means that the key materials advantage of silicon for CMOS circuits is gone. Introduction of high-k oxides into Si ICs makes the perspectives of III-V integration significantly more feasible.
- Further scaling of transistors relaxes some of the requirements to the gate stack, such as interface trap density,  $D_{it}$ . In fact, due to increased oxide capacitance, the circuits can handle much higher levels of  $D_{it}$  which previously considered as detrimental.
- Si IC companies, mainly INTEL and IBM and their consortia, have shown interest beyond just research.

Apparently, there are still a lot of challenges to be overcome before manufacturing becomes viable. According to Robert Chau, Director of transistor research and nanotechnology at INTEL Corporation, there are following four major challenges (CSIC 2005 Tech. Digest): (1) compatible high-quality gate dielectric; (2) scaling with acceptable  $I_{ON}/I_{OFF}$  ratio; (3) p-channel with a reasonable transport; and

(4) integration onto Si substrate. This book addresses research covering the first three of these challenges. We believe the integration with Si involves significantly different materials problems, than those covered in this book. In addition, there are a few good books and reviews on this topic (E. Towe (Ed.) *Heterogeneous optoelectronics integration*, SPIE Press, 2000; E. Fitzgerald, *ECS Trans.* 19, 345, 2009; F. Letertre, *AIP Conf. Proc.* 1068, 185, 2008).

The book begins with a concise historic review (Chap. 1) of challenges and breakthroughs that led to the evolution of today's III-V MOSFETs. Two chapters on device simulations (Chaps. 2, 3) present performance analysis of MOSFETs with different III-V channels with the focus on benefits, potential showstoppers, and novel promising device structures (Chap. 2); and device physics and technology issues for InGaAs HEMTs based on close comparison with recent experimental results (Chap. 3). The chapters on *ab initio* density function theory simulations include concise introduction into DFT (Chaps. 4, 5) and simulation results on oxide/III-V interfaces with a particular focus on amorphous oxides (Chap. 5), and on bulk and surface properties of  $\text{HfO}_2$  and  $\text{ZrO}_2$  high-k oxides and metal-oxide interfaces (Chap. 4). Chapter 6 reviews the interfacial chemistry of III-V's, with particular attention to native and deposited oxide gate dielectrics, and correlation with electrical properties of these interfaces. Chapter 7 proposes an empirical model to correlate the experimental work on III-V MOSFETs with the existing oxide/III-V interface models. It follows by six chapters (Chaps. 8–13) on high-k/III-V integration and device work on III-V MOSFETs. Chapter 8 begins with comparison of HEMT for logic applications to MOSFET technology with emphasis on current transport and interface passivation. Chapter 9 presents the new progress on InGaAs, Ge and GaN MOSFETs with MBE  $\text{Ga}_2\text{O}_3$  ( $\text{Gd}_2\text{O}_3$ ) or ALD  $\text{Al}_2\text{O}_3$  as gate dielectrics. Chapter 9 discusses the critical process issues for self-aligned III-V MOSFET and presents the device work on self-aligned GaAs enhancement-mode MOSFETs using regrown source and drain regions. Detailed work on  $\text{HfO}_2$  with silicon interface passivation on various III-V substrates are summarized in Chap. 11. The new progress on III-V p-channel MOSFETs, one of the grand challenges in III-V CMOS technology, is reviewed in Chap. 12. Chapter 13 describes materials growth, deposition and fabrication technology, device characteristics, reliability, and applications of insulated gate group III-nitride field effect transistors. The book is ended by the Chap. 14 as a III-V circuit chapter, where the complete technology-circuit assessment of III-V FETs and the co-design approach from the device/SPICE models, logic/memory circuit analysis and technology requirements are presented.

After over 40 years of success of Si/ $\text{SiO}_2$  material system in digital circuits, high-k oxides became attractive for further CMOS scaling at the end of 1990s and instigated explosive research growth that resulted in its successful commercialization. We hope that the III-V research is currently at a similar stage as high-k's were in 1990s, and that the combined efforts in academia and industry will make the long-standing GaAs MOSFET dream a commercial technology.

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Serge Oktyabrsky and Peide D. Ye

# Contents

<b>1 Non-Silicon MOSFET Technology: A Long Time Coming</b>	<b>1</b>
Jerry M. Woodall	
1.1 Introduction	1
1.2 Brief and Non-Comprehensive History of the NSMOSFET	2
1.3 Surface Fermi Level Pinning: The Bane of NSMOSFET Technology Development	3
1.4 Concluding Remarks	6
References	6
<b>2 Properties and Trade-Offs of Compound Semiconductor MOSFETs</b>	<b>7</b>
Tejas Krishnamohan, Donghyun Kim and Krishna C. Saraswat	
2.1 Introduction	7
2.2 Simulation Framework	10
2.3 Power-Performance Tradeoffs in Binary III-V Materials (GaAs, InAs, InP and InSb) vs. Si and Ge	15
2.4 Power-Performance of Strained Ternary III-V Material ( $\text{In}_x\text{Ga}_{1-x}\text{As}$ )	19
2.5 Strained III-V for p-MOSFETs	22
2.6 Novel Device Structure and Parasitics	24
2.7 Conclusion	27
References	27
<b>3 Device Physics and Performance Potential of III-V Field-Effect Transistors</b>	<b>31</b>
Yang Liu, Himadri S. Pal, Mark S. Lundstrom, Dae-Hyun Kim, Jesús A. del Alamo and Dimitri A. Antoniadis	
3.1 Introduction	31
3.2 InGaAs HEMTs	32
3.3 Discussion	36
3.4 Conclusions	46
References	47

<b>4</b>	<b>Theory of <math>\text{HfO}_2</math>-Based High-k Dielectric Gate Stacks</b>	<b>51</b>
	Alexander A. Demkov, Xuhui Luo and Onise Sharia	
4.1	Introduction	51
4.2	Theoretical Background	52
4.3	Properties of Bulk Hafnia and Zirconia	57
4.4	Surfaces	71
4.5	Band Alignment at Hafnia Interfaces	81
4.6	Conclusions	89
	References	89
<b>5</b>	<b>Density Functional Theory Simulations of High-k Oxides on III-V Semiconductors</b>	<b>93</b>
	Evgueni A. Chagarov and Andrew C. Kummel	
5.1	Introduction	93
5.2	Methodology of DFT Simulations of High-k Oxides on Semiconductor Substrates	96
5.3	DFT Simulations of High-k Oxides on Si/Ge Substrates	106
5.4	Generation of Amorphous High-k Oxide Samples by Hybrid Classical-DFT Molecular Dynamics Computer Simulations	112
5.5	The Current Progress in DFT Simulations of High-k Oxide/III-V Semiconductor Stacks	118
5.6	Summary	126
	References	126
<b>6</b>	<b>Interfacial Chemistry of Oxides on III-V Compound Semiconductors</b>	<b>131</b>
	Marko Milojevic, Christopher L. Hinkle, Eric M. Vogel and Robert M. Wallace	
6.1	Introduction	131
6.2	Surfaces of III-V MOSFET Semiconductor Candidates	132
6.3	Oxide Formation (Native and Thermal)	138
6.4	Oxide Deposition on III-V Substrates	146
6.5	Electrical Behavior of Oxides on III-V and Interfacial Chemistry	156
6.6	Conclusions	165
	References	165
<b>7</b>	<b>Atomic-Layer Deposited High-k/III-V Metal-Oxide-Semiconductor Devices and Correlated Empirical Model</b>	<b>173</b>
	Peide D. Ye, Yi Xuan, Yanqing Wu and Min Xu	
7.1	Introduction	173
7.2	History and Current Status	174
7.3	Empirical Model for III-V MOS Interfaces	178
7.4	Experiments on High-k/III-V MOSFETs	181
7.5	Conclusion	188
	References	189



<b>8</b>	<b>Materials and Technologies for III-V MOSFETs</b>	195
	Serge Oktyabrsky, Yoshio Nishi, Sergei Koveshnikov, Wei-E Wang, Niti Goel and Wilman Tsai	
8.1	Introduction	195
8.2	III-V HEMTs for Digital Applications	196
8.3	Challenges for III-V MOSFETs	207
8.4	Mobility in Buried Quantum Well Channel	208
8.5	Interface Passivation Technologies	210
8.6	Summary	237
	References	238
<b>9</b>	<b>InGaAs, Ge, and GaN Metal-Oxide-Semiconductor Devices with High-k Dielectrics for Science and Technology Beyond Si CMOS</b>	251
	M. Hong, J. Kwo, T. D. Lin, M. L. Huang, W. C. Lee and P. Chang	
9.1	Introduction	251
9.2	Material Growth, Device Fabrication, and Measurement	253
9.3	Devices	255
9.4	Interfacial Chemical Properties	266
9.5	Energy-Band Parameters	268
9.6	Thickness Scalability of $\text{Ga}_2\text{O}_3(\text{Gd}_2\text{O}_3)$ on InGaAs with Low $D_{it}$ , Low Leakage Currents, and High-Temperature Thermodynamic Stability	272
9.7	Interface Trap Densities and Efficiency of Fermi-Level Movement	274
9.8	Conclusion	279
	References	280
<b>10</b>	<b>Sub-100 nm Gate III-V MOSFET for Digital Applications</b>	285
	K. Y. (Norman) Cheng, Milton Feng, Donald Cheng and Chichih Liao	
10.1	Introduction	285
10.2	MOSFET Figures of Merit for Digital Applications	286
10.3	Selection of III-V Channel Materials	290
10.4	Self-Aligned III-V MOSFET Structures	294
10.5	Benchmark of III-V FET with Si CMOS	299
10.6	Outlook and Conclusions	302
	References	303
<b>11</b>	<b>Electrical and Material Characteristics of Hafnium Oxide with Silicon Interface Passivation on III-V Substrate for Future Scaled CMOS Technology</b>	307
	Injo Ok and Jack C. Lee	
11.1	Introduction	307
11.2	MOSCAPs and MOSFETs on GaAs with Si, SiGe Interface Passivation Layer (IPL)	309
11.3	MOSCAPs and MOSFETs on InGaAs with Si IPL	334

11.4	MOSCAPs and Self-Aligned n-channel MOSFETs on InP Channel Materials with Si IPL . . . . .	342
11.5	Conclusions . . . . .	346
	References . . . . .	347
<b>12</b>	<b>p-type Channel Field-Effect Transistors . . . . .</b>	<b>349</b>
	Serge Oktyabrsky . . . . .	
12.1	Introduction . . . . .	349
12.2	Low-Field Hole Mobility in Bulk Semiconductors . . . . .	351
12.3	p-channel: Figures of Merit with Scaling of Channel Length . . . . .	353
12.4	Strained Quantum Wells . . . . .	355
12.5	p-channel HFETs . . . . .	364
12.6	p-type MOSFETs . . . . .	370
12.7	Conclusions . . . . .	372
	References . . . . .	372
<b>13</b>	<b>Insulated Gate Nitride-Based Field Effect Transistors . . . . .</b>	<b>379</b>
	M. Shur, G. Simin, S. Romyantsev, R. Jain and R. Gaska . . . . .	
13.1	Introduction . . . . .	379
13.2	Materials Growth and Deposition Technologies . . . . .	381
13.3	Transport Properties . . . . .	389
13.4	Device Design and Fabrication . . . . .	395
13.5	Device Characteristics . . . . .	397
13.6	Non-Ideal Effects and Reliability . . . . .	404
13.7	Applications and Performance . . . . .	406
13.8	Future Trends: From Megawatts to Terahertz . . . . .	414
	References . . . . .	416
<b>14</b>	<b>Technology/Circuit Co-Design for III-V FETs . . . . .</b>	<b>423</b>
	Jaydeep P. Kulkarni and Kaushik Roy . . . . .	
14.1	Introduction . . . . .	423
14.2	Device/SPICE Models . . . . .	425
14.3	Logic Circuit Analysis . . . . .	428
14.4	Memory Circuit Analysis . . . . .	435
14.5	Application Space of III-V QWFETs . . . . .	439
14.6	Conclusions . . . . .	439
	References . . . . .	440
	<b>Index . . . . .</b>	<b>443</b>

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# Chapter 1

## Non-Silicon MOSFET Technology: A Long Time Coming

Jerry M. Woodall

**Abstract** A summary of the important materials science issues associated with the realization of viable III-V MOSFET technologies is presented. The key science breakthrough was the unambiguous identification of which components of the non-stoichiometric native oxides were responsible for surface Fermi level pinning (FLP). The components that cause FLP are the anion oxides and the elemental anion associated with a particular III-V compound semiconductor. For GaAs, these are  $\text{As}_2\text{O}_3$  and elemental As respectively. The physics of FLP is also applicable to Schottky barriers. Although many attempts were made to explain FLP, the most comprehensive theory is that the elemental anion acts to cause FLP via its Schottky barrier workfunction. During the past decade several technologies have succeeded in mitigating these chemical barriers and III-V MOSFET technology is now a component of the MOSFET menu.

### 1.1 Introduction

The purpose of this chapter is to provide the reader with a brief, non-comprehensive overview of the history, scientific and technological barriers, pre-device solutions, and seminal research results that led to the evolution of today's non-silicon MOSFET (NSMOSFET) technology.

If you are living on planet Earth, you must know that silicon MOSFET (SMOSFET) technology, with a 2008 worldwide chip sales of more than \$250 billion, is essentially the only semiconductor technology used by all electronics based industries. By contrast, the total 2008 sales of *all* compound semiconductor devices and chips are about \$20 billion, and most of this revenue was generated by heterojunction based photonic devices and chips. In contrast, none of the revenue was produced by NSMOSFETs sales (save some devices sold for testing and military applications).

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Why is Si technology the dominant semiconductor technology? To answer this at the highest level, let me tell the reader the answer I give my undergraduate students during the first lecture of Purdue's core semiconductor course. Even though Si is an inferior electronic and photonic material compared to, for example, GaAs, Si is still king because Si is cheap and the rust on Si is electronically exquisite, whereas the rust on nearly all compound semiconductors of interest is either inferior or non-functional electronically. In other words, both price-performance advantages of SMOSFET technology and the lack of a viable NSMOSFET technology during the early R&D efforts have hampered its development. This chapter will discuss why the electronic and chemical properties of compound semiconductor rust were not suitable for the "O" material for NSMOSFETs.

Another question, possibly rhetorical, comes to mind at this point. Even if the application specific performance of NSMOSFET technology could be far superior to planned performance for SMOSFET technology, will it supplant Si technology? Is it too little or too late? This situation can be likened to the current global energy crisis. Let us equate Si technology with fossil fuel technology (ignoring carbon footprint issues). Both are the overwhelming dominant incumbents. Now let us equate alternative solar energy technology with NSMOSFET technology. The central question for both fossil fuel and Si technology is whether there is a business model for solar energy technology and NSMOSFET technology that will result in supplanting the current fossil fuel and Si incumbents. Or, will Si, for example, stay on a revised "Moore's Law" path? This question will be addressed in a later chapter in this book.

## 1.2 Brief and Non-Comprehensive History of the NSMOSFET

Any discussion of the history of any MOSFET technology, or of any other transistor technology, must begin with the Heil and Lilienfeld Patents [1, 2]. Examination of Heil's patent clearly indicates that a MOSFET was being described. Amusingly, Heil's 1934 patent date is 13 years before the commonly accepted birth date of the transistor. It is less amusing to note that neither Heil nor Lilienfeld were included in the Nobel Prize for the invention of the transistor.

The next seminal event, also not recognized by the Nobel Committee, was the first public report of the SMOSFET by Kang and Atalla [3]. This report was seminal in that the SMOSFET became the dominant material for commercial MOSFETs. Very rarely does the early work ever evolve into the dominant technology.

The 1960s and 1970s were a period of intense development and rapid progress of SMOSFET technology. Hundreds of worldwide workers in corporate and university laboratories contributed to this progress. However, except for isolated successes limited to laboratory scale III-V and II-VI compound thin film transistor (TFT) devices, attempts during this period to develop a NSMOSFET technology were essentially unsuccessful. An exception to this notable lack of progress in NSMOSFET development was the work of Brody and Kunig, who, in 1966, realized both