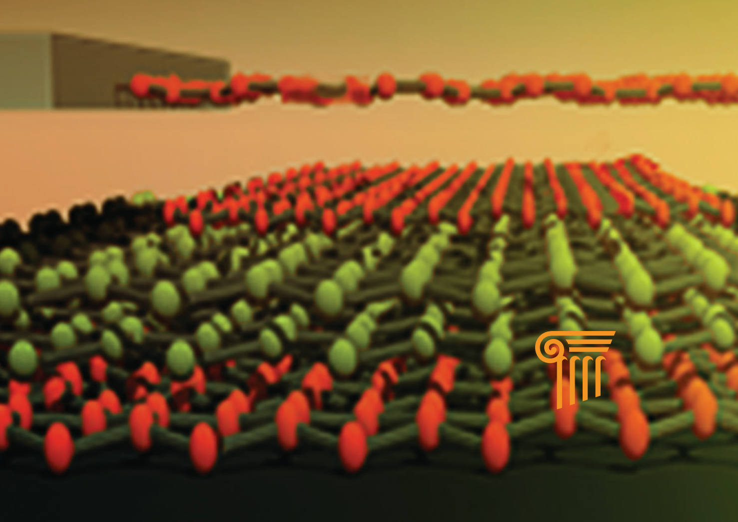
Jenny Stanford Series on Intelligent Nanosystems Volume 4

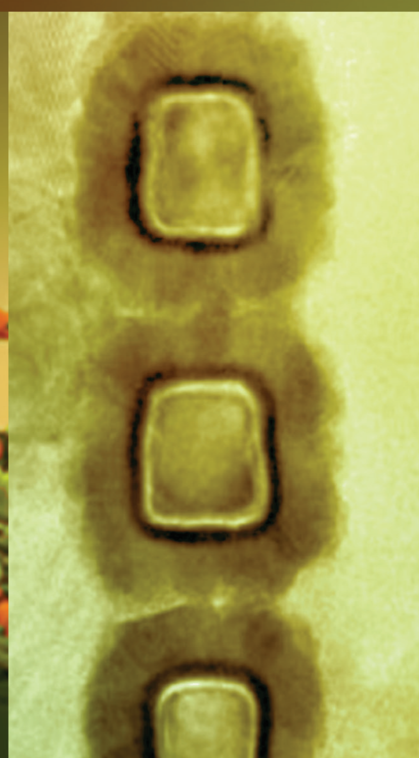
Convergence of More Moore, More Than Moore, and Beyond Moore

Materials, Devices, and Nanosystems

edited by

Simon Deleonibus





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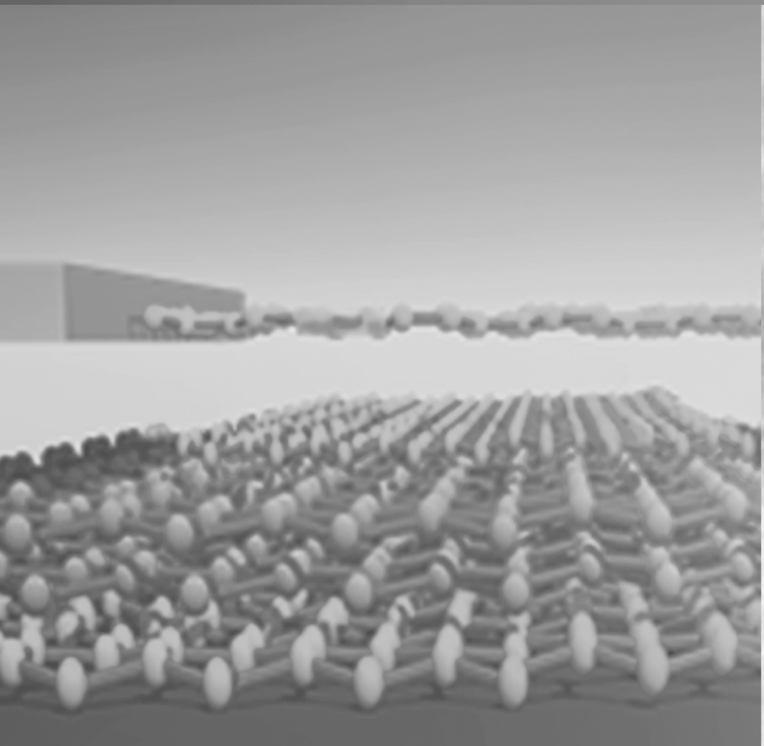

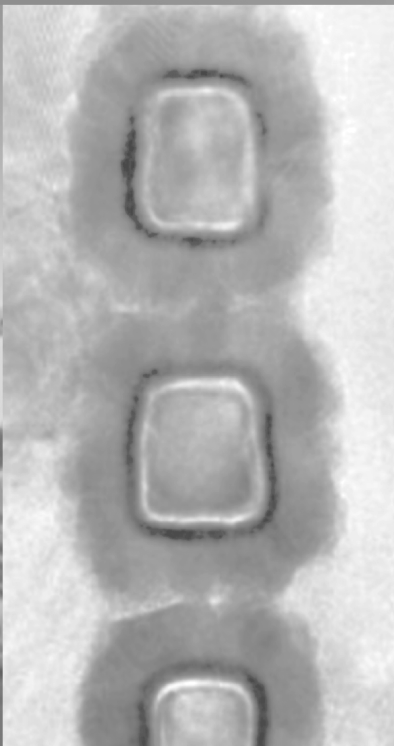

Jenny Stanford Series on Intelligent Nanosystems

Series Editor

Simon Deleonibus

Titles in the Series

Vol. 1
Intelligent Integrated Systems: Devices, Technologies, and Architectures

Simon Deleonibus, ed.

2014

978-981-4411-42-4 (Hardcover)
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Vol. 2
Integrated Nanodevice and Nanosystem Fabrication: Materials, Techniques, and New Opportunities

Simon Deleonibus, ed.

2017

978-981-4774-22-2 (Hardcover)
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Vol. 3
Emerging Devices for Low-Power and High-Performance Nanosystems: Physics, Novel Functions, and Data Processing

Simon Deleonibus, ed.

2018

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Convergence of More Moore, More Than Moore, and Beyond Moore: Materials, Devices, and Nanosystems

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Preface

A few years ago, Pan Stanford Publishing (Singapore) invited me to edit the *Pan Stanford Series on Intelligent Nanosystems* which was recently renamed *Jenny Stanford Series on Intelligent Nanosystems.* The series is now quite successful and attracts many internationally renowned researchers as authors on latest and hottest topics on nanoelectronics and nanosystems. The notion of system has been evolving in the past and will continue to evolve even in future technologies. In the field of nanoelectronics and nanosystems, downscaling of components has made it possible to integrate more and more complex functions in various handheld devices and to serve humanity better. As an example, the telephone, a system built on a complex technology, was owned by a few people until the middle of the 20th century: in most cases, it was a fixed home or office appliance. Nowadays, telephone is a handheld and nomadic: moreover, one can do so many things other than just placing a call with a mobile phone! It has become a companion for all human beings, assisting them in all daily life activities. It has also become a ubiquitous channel to communicate and exchange services in all aspects of personal and collective activities, such as information, education, leisure, and multimodal communication. It has taken such a space in our lives that its societal impact and its ethical use can be questioned or needs to be regulated.

Challenges are ahead of us to meet the growing demand for energy efficient and sustainable technologies, not necessarily available with today's current schemes. In such a context, alternative devices and approaches are benchmarked for sensing, actuating, data storage, and processing. This evolution already requests new technology-integration paradigms, which leave the floor to integrated intelligent nanosystems to match a convergence between the "more Moore," "more than Moore," and "beyond Moore" domains: this path guides the transition from the age of nanoelectronics to the diversified nanosystems era. The adoption of new nanofunctions for augmented nanosystems will result from such a move. Low power consumption and high performance will be requested throughout the value chain, with the help of 2D/3D hybrid and heterogeneous cointegration of

CMOS, memories, sensors, actuators, and their environment-friendly compatible packaging. This is what this book series aims to highlight. The first volume of this series, published in April 2014, contains 13 chapters and is dedicated to *Intelligent Integrated Systems: Devices, Technologies, and Architectures.* The second volume, published in November 2017, contains 8 chapters and is dedicated to *Integrated Nanodevice and Nanosystem Fabrication: Materials, Techniques, and New Opportunities.* The third volume, published in September 2019, contains 9 chapters and is dedicated to *Emerging Devices for Low-Power and High-Performance Nanosystems: Physics, Novel Functions, and Data Processing.* The fourth volume, contains 7 chapters and is entitled *Convergence of More Moore, More Than Moore, and Beyond Moore: Materials, Devices, and Nanosystems*

The introduction of the book claims the necessity to search for sustainable and energy-efficient technology convergence in the "Internet of Everything" era. The book is divided in two parts. Part 1 (Chapters 1 to 4), titled *From Nanoelectronics to Diversified Nanosystems,* reports on the era of sustainable and energy-efficient nanoelectronics and nanosystems, the transition from 2D to 3D non-volatile memories, the emerging 3D resistive memories, and SOI technologies for radio-frequency and millimeter-wave applications. In Part 2 (Chapters 5 to 7), titled *Nanofunctions for Augmented Nanosystems*, graphene nanoelectromechanical (NEM) switches ultimately downscaled to single molecule and zeptogram mass sensors, self-powered 3D nanosensor systems for mechanical interfacing applications enabled by the fundamental principles of piezotronic effect and triboelectric nanogenerators, as well as the miniaturization and packaging of implantable biomedical silicon devices are reviewed.

The book series, including this book, is intended for graduate students, educators, researchers, and engineers. It gives readers the opportunity to enjoy the tutorial reports of highest-level written by world-famous authors on the most advanced research results. I am happy to deliver such a collection to them, and I am sure, it will be useful to boost their own research or simply their curiosity and knowledge.

Simon Deleonibus

Grenoble, France

August 12, 2020

Acknowledgments

I wish to congratulate my co-authors of the seven chapters of *Convergence of More Moore, More Than Moore, and Beyond Moore: Materials, Devices, and Nanosystems*, the fourth volume of the *Jenny Stanford Series on Intelligent Nanosystems*, for the results of invaluable quality of their research as well as for their excellent contributions, including a review of the state of the art in their respective fields. As worldwide recognized researchers and professionals belonging to top-level renowned universities, institutes, or companies, their determination and energy have been of utmost importance to the success of this ambitious project.

It is a great honor to receive the support to promote the book from Prof. Chenming Hu, University of California at Berkeley, USA; Prof. Mitsumasa Koyanagi, Tohoku University, Japan; Prof. Shunri Oda, Tokyo Institute of Technology, Japan; and Prof. Steve Chung, National Chiao Tung University, Taiwan. Their influence in the nanoelectronics, nanotechnology, and nanoscience world underlines the high scientific level of the different contributions.

I have special thanks to address to Ms. Jenny Rompas, Mr. Stanford Chong, Ms. Shivani Sharma, and staff members of Jenny Stanford Publishing for their assistance throughout the process, from defining the book content to the final edition, and the promotion of this book. I wish to deeply thank them for their trust and enthusiasm during the many years of collaboration throughout the publication process of this book series.

I wish to highlight the constant support and patience of my wife, Geneviève, and my son, Tristan, as well as the encouragement from my friends and colleagues while I worked on this book series. Their positive attention was essential to motivate me to overcome the challenges of the project. I wish to dedicate this work to them.

Simon Deleonibus

Past Chief Scientist CEA-Leti

Fellow IEEE, Fellow Electrochemical Society, CEA Research Director

Invited Editor at Jenny Stanford Publishing

Introduction

The Technology Convergence for a Sustainable and Energy-Efficient Internet of Everything Era

Simon Deleonibus
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The era of sustainable and energy efficient nanoelectronics and nanosystems has come. The research and development on scalable and 3D-integrated diversified functions, together with new computing architectures is in full swing. Besides data processing, data storage, new sensing modes, and communication capabilities need a revision of process architectures to enable the heterogeneous cointegration of add-on devices with CMOS. The new defined functions and paradigms open the way to augmented nanosystems that will appear to serve the future Internet of Things and Everything. The necessity of future breakthroughs will request the study of new devices, circuits, and computing architectures and to take new unexplored paths, including new materials and integration schemes as well.

Convergence of More Moore, More Than Moore, and Beyond Moore: Materials, Devices, and Nanosystems is the fourth volume in the Jenny Stanford (formerly Pan Stanford) Series on Intelligent Nanosystems. The book reviews the essential modules to build diversified nanosystems based on nanoelectronics and its diversification as well as the way they define nanofunctions for augmented nanosystems. The volume features seven chapters divided in two parts entitled:

Part I From Nanoelectronics to Diversified Nanosystems, featuring Chapters 1 to 4, and

Part II Nanofunctions for Augmented Nanosystems, including Chapters 5 to 7.

Chapter 1 entitled "The Era of Sustainable and Energy Efficient Nanoelectronics and Nanosystems" by Simon Deleonibus, past chief scientist of Université Grenoble Alpes, CEA-Leti, France, presents the solutions to integrate thin film–based nanoelectronic devices, necessary to design the future challenging architectures and systems. Fabricating circuits with increasing complexity in high volume will appeal for zero intrinsic variability, drastically enhanced energy efficiency, and materials consumption moderation. Three–dimensional (3D) integration of hybrid, heterogeneous technologies at the device, functional, and system levels will drive future innovations. The maximization of energy efficiency of cointegrated low power and high-performance logic, memory, and nanosystems devices will significantly impact the world energy saving balance. The future of nanoelectronics will need to be energy and variability efficiency (E.V.E.) conscious.

The challenges of the increasing demand and achievements of high density memories are reviewed in the following Chapters 2 and 3, whereas Chapter 4 focuses on the radio frequency (RF) communication challenges at the components level.

Chapter 2 entitled "From 2D to 3D Nonvolatile Memories" by Akira Goda of Micron Technology Inc., USA, reviews the successful scaling of non-volatile memories; thanks to the transition of 2D to 3D integration of NAND-type memory cells, while maintaining a large physical cell size with a gate-all-around vertical transistor architecture. The memory density has increased by more than 1000 times over the past two decades, reaching 1 Tb die capacity in 2018 and featuring 4 bits/memory cell and tremendously reduces the bit cost scaling.

In **Chapter 3,** Qing Luo and Ming Liu of the Institute of Microelectronics of the Chinese Academy of Sciences, PR China, give a comprehensive outlook of the "Three-Dimensional Vertical Resistive Random Access Memories." These devices can reach very high density; thanks to the implementation of selectors and a self-selective, cells-based architecture. Their potential application as storage class memories are reviewed and assessed.

In our rapidly growing communication world, the RF performance of nanoelectronic devices and circuits is listed among the earliest demand by circuit design. Martin Rack and Jean-Pierre Raskin of Université Catholique de Louvain, Belgium, review the breakthroughs in the field in **Chapter 4** "Silicon on Insulator Technologies for RF and Millimeter-Wave Applications." Thanks to the silicon on insulator (SOI)'s low-parasitic architecture and good electrostatics that enable to achieve high oscillation and cut-off frequencies in the range of 400 GHz through this technology. At the RF-IC level, a review is made to reveal the position of SOI for key RF and millimeter-wave circuits (switches, LNAs, and PAs). The existing flavors of SOI substrates are reviewed, along with the promising next-generation substrate solutions. SOI is shown to be a prime candidate not only for high-performance millimeter-wave and 5G applications, but also for low-power RF Internet of Things (IoT).

In Chapters 5 to 7, breakthrough ideas to integrate new materials and devices for sensing applications or harvest energy in future 3D autonomous biocompatible nanosystems are put forward.

Graphene nanoelectromechanical (GNEM) switches and their extreme sensing capability as a single-molecule sensor and zeptogram mass detector are reviewed by Manoharan Muruganathan and Hiroshi Mizuta of Japan Advanced Institute of Science and Technology, Japan, and Hitachi Cambridge Laboratory, UK, respectively. In **Chapter 5,** entitled "Graphene Nanoelectromechanical Switch: Ultimate Downscaled NEM Actuators to Single-Molecule and Zeptogram Mass Sensors," they demonstrate that due to its excellent mechanical stability, high surface-to-volume ratio, and low-noise characteristics, graphene is an ideal platform to realize high-performance NEM switches and sensors. They assess the operating principles of the graphene NEM-based extreme sensors for single CO_2 molecular detection and zeptogram mass detection.

Energy efficiency is a strong requirement for the development of future high-performance autonomous nanosystems, especially if they are wearable and integrated in the human body. In **Chapter 6** on "Self-Powered 3D Nanosensor Systems for Mechanical Interfacing Applications," Wenzhuo Wu and Zhong Lin Wang of Purdue University and Georgia Institute of Technology, USA, respectively, demonstrate how piezotronic effects and triboelectric nanogenerators can be used to harvest energy from the environment through mechanical interfacing. They discuss their integration by following 3D schemes.

Aging population and healthcare are strong drivers for research and miniaturization of micro- and nanosystems. Thus, scaling and packaging of implantable biomedical silicon devices are serious issues to face in the packaging of integrated circuits as their demand keeps increasing. **Chapter 7** entitled "Miniaturization and Packaging of Implantable Biomedical Silicon Devices," by Jean-Charles Souriau of Université Grenoble Alpes, CEA-Leti, France, presents a new approach on the encapsulation of electronic components in a reduced, form factor silicon box using wafer-level microelectronic processing, capable of bio-stability and biocompatibility. It assesses the performances of several passivation strategies in an ultimate direct wafer-level encapsulation scheme.