NANOMAGNETIC AND SPINTRONIC DEVICES FOR ENERGY-EFFICIENT MEMORY AND COMPUTING

In memory of my late great-uncle, N. Seshagiri, who inspired my career in science and technology

Jayasimha Atulasimha

In memory of my uncle, Dalumama

Supriyo Bandyopadhyay

NANOMAGNETIC AND SPINTRONIC DEVICES FOR ENERGY-EFFICIENT MEMORY AND COMPUTING

Edited by

Jayasimha Atulasimha and Supriyo Bandyopadhyay

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Cover image: The cover shows magnetic force micrographs of an array of 100-nm sized nanomagnets exhibiting single-domain behavior. Image courtesy of the Atulasimha group and Bandyopadhyay group.

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About the Editors and Acknowledgments

Jayasimha Atulasimha

Jayasimha Atulasimha is Qimonda Associate Professor of Mechanical and Nuclear Engineering with a courtesy appointment in Electrical and Computer Engineering at the Virginia Commonwealth University, where he directs the Magnetism, Magnetic Materials and Magnetic Devices (M^3) laboratory. He has authored or coauthored over 60 scientific articles including more than 40 journal publications on magnetostrictive materials, magnetization dynamics, and nanomagnetic computing and has given several invited talks at conferences, workshops and universities in the USA and abroad on these topics. His research interests include nanomagnetism, spintronics, magnetostrictive materials and nanomagnet-based computing devices. He received the NSF CAREER Award for 2013–2018. He currently serves on the Technical Committees for Spintronics, IEEE Nanotechnology Council, ASME Adaptive Structures and Material Systems, Device Research Conference (DRC), and as a Focus Topic organizer for the APS topical group on magnetism (GMAG). He is a member of ASME, APS and an IEEE Senior Member.

Supriyo Bandyopadhyay

Supriyo Bandyopadhyay is Commonwealth Professor in the Department of Electrical and Computer Engineering in Virginia Commonwealth University, Richmond, Virginia, USA, where he directs the Quantum Device Laboratory. His research interests are in broad areas of nanotechnology and focus on spintronics, nanomagnetism, energy-efficient and noncharge-based computing paradigms, optical properties of nanostructures, and self-assembly based nanosynthesis. He is the author/coauthor of over 300 peer reviewed research publications and has given over 100 invited or keynote talks in conferences, workshops and colloquia across four continents. He currently serves as the Chair of the Technical Committee on Spintronics within the Nanotechnology Council of the Institute of Electrical and Electronics Engineers (IEEE) and in the past served as the Chair of the Technical Committee on Compound Semiconductor Devices within the Electron Device Society of IEEE. He has served as an IEEE Distinguished Lecturer and also as a Vice President of the IEEE Nanotechnology Council. He is the winner of the Distinguished Scholarship Award at Virginia Commonwealth University, which is the highest award given by the university for scholarship to one faculty member each year, and

also won the faculty research award, the faculty interdisciplinary research award and the faculty service award from the College of Engineering at University of Nebraska where he was employed prior to coming to Virginia Commonwealth University. He currently serves on the editorial boards of six international journals and served on the editorial boards of seven other journals in the past. Dr Bandyopadhyay is a Fellow of the Institute of Electrical and Electronics Engineers, American Physical Society, Institute of Physics, the Electrochemical Society and the American Association for the Advancement of Science.

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List of Contributors

Nikhil Bhandari
Spintronics and Vacuum Nanoelectronics Laboratory
University of Cincinnati
Cincinnati, OH, USA

Debanjan Bhowmik
Department of Electrical Engineering and Computer Sciences
University of California Berkeley
Berkeley, CA, USA

Ayan K. Biswas
Department of Electrical and Computer Engineering
Virginia Commonwealth University
Richmond, VA, USA

Marc Cahay
Spintronics and Vacuum Nanoelectronics Laboratory
University of Cincinnati
Cincinnati, OH, USA;
Physics Department
University of Cincinnati
Cincinnati, OH, USA

James Charles
School of Electrical Engineering
Purdue University
West Lafayette, IN, USA

Noel D'Souza
Department of Mechanical and Nuclear Engineering
Virginia Commonwealth University
Richmond, VA, USA

Y. Dusch
LIA LICS/LEMAC, IEMN UMR CNRS 8520, Univ. Lille, Centrale Lille
Lille, France

Maitreya Dutta
Spintronics and Vacuum Nanoelectronics Laboratory
University of Cincinnati
Cincinnati, OH, USA

Avik W. Ghosh
Charles L Brown School of Electrical and Computer Engineering
University of Virginia
Charlottesville, VA, USA

S. Giordano
LIA LICS/LEMAC, IEMN UMR CNRS 8520, Univ. Lille, Centrale Lille
Lille, France

S.T. Herbert
Department of Physics
Xavier University
Cincinnati, OH, USA

Mahdi Jamali
University of Minnesota
Minneapolis, MN, USA

Santosh Khasanvis
University of Massachusetts Amherst
Amherst, MA, USA

Alexander Khitun
University of California
Riverside, CA, USA

A. Klimov
International Associated Laboratory LIA LEMAC
Lille, France;
Moscow Institute of Radio Engineering and Automation MIREA
Moscow, Russia;
V.A. Kotelnikov Institute of Radioengineering and Electronics
Moscow, Russia

Alexander Kozhanov
Georgia State University
Atlanta, GA, USA

OukJae Lee
Department of Electrical Engineering and Computer Sciences
University of California Berkeley
Berkeley, CA, USA

Csaba Andras Moritz
University of Massachusetts Amherst
Amherst, MA, USA

Kamaram Munira
Center for Materials for Information Technology
University of Alabama
Tuscaloosa, AL, USA

P. Pernod
LIA LICS/LEMAC, IEMN UMR CNRS 8520, Univ. Lille, Centrale Lille
Lille, France

V. Preobrazhensky
LIA LICS/LEMAC, IEMN UMR CNRS 8520, Univ. Lille, Centrale Lille
Lille, France;
A.M. Prokhorov General Physics Institute RAS
Moscow, Russia

Mostafizur Rahman
University of Massachusetts Amherst
Amherst, MA, USA

Ivan Rungger
School of Physics, AMBER and CRANN Institute
Trinity College
Dublin, Ireland

Sayeef Salahuddin
Department of Electrical Engineering and Computer Sciences
University of California Berkeley
Berkeley, CA, USA

Stefano Sanvito
Center for Materials for Information Technology
University of Alabama
Tuscaloosa, AL, USA

Prasad Shabadi
University of Massachusetts Amherst
Amherst, MA, USA
Marvell Semiconductors

Yusuke Shuto
Imaging Science and Engineering Laboratory
Tokyo Institute of Technology
4259 Nagatsuta, Midori-ku, Yokohama, Japan

Angeline Klemm Smith
University of Minnesota,
Minneapolis, MN, USA

Maria Stamenova
School of Physics, AMBER and CRANN Institute
Trinity College
Dublin, Ireland

Satoshi Sugahara
Imaging Science and Engineering Laboratory
Tokyo Institute of Technology
4259 Nagatsuta, Midori-ku, Yokohama, Japan

N. Tiercelin
LIA LICS/LEMAC, IEMN UMR CNRS 8520, Univ. Lille, Centrale Lille
Lille, France

Junjun Wan
Intel Corporation
Hillsboro, OR, USA

Jian-Ping Wang
University of Minnesota
Minneapolis, MN, USA

Yunkun Xie
Charles L Brown School of Electrical and Computer Engineering
University of Virginia
Charlottesville, VA, USA

Shuu'ichirou Yamamoto
Imaging Science and Engineering Laboratory
Tokyo Institute of Technology
4259 Nagatsuta, Midori-ku, Yokohama, Japan

Long You
Department of Electrical Engineering and Computer Sciences
University of California Berkeley
Berkeley, CA, USA

Zhengyang Zhao
University of Minnesota
Minneapolis, MN, USA

Foreword

When I started out on my career, CMOS technology had just begun its domination in electronics. Although there are major challenges in continued scaling, no other technology was expected to be able to compete with CMOS commercially in the near future. However, the research community had always been interested in looking beyond CMOS and searching for alternative technologies. I was very fortunate to be surrounded by wise mentors and brilliant colleagues, who ultimately convinced me it would be fun to be in the arena of "beyond CMOS technologies." On many occasions I wished somebody had written a book summarizing the most promising developments, saving professionals and students the time and aggravation of sifting through a plethora of many approaches. The fact that Jayasimha Atulasimha and Supriyo Bandyopadhyay are doing just that, putting together a collection of the latest and most promising developments in spintronics, is going to benefit not only young students and researchers new to the field, but will also provide a convenient reference for experts and experienced researchers to build their discoveries upon.

The field of spintronics has enjoyed rapid progress during the last decade, mostly due to the major challenge of excessive power dissipation in further CMOS scaling, which threatens perhaps a complete halt to scaling in the near future. As any active researcher in this field will tell you, the race to be the first to discover novel devices far beyond CMOS applications is both exhilarating as well as exhausting. It is therefore with great pleasure and honor that I am writing this foreword to introduce you to this timely treatise on the latest developments in this field, edited by recognized experts as well as my friends and colleagues, Supriyo Bandyopadhyay and Jayasimha Atulasimha.

This new book delivers a summary of the latest developments in spintronics in a way that is pleasantly digestible for any graduate level student and beyond, aspiring to excel in this field.

Professor Kang L. Wang
Distinguished Professor and Raytheon Chair in Electrical Engineering
University of California, Los Angeles

Preface

The complementary metal-oxide semiconductor (CMOS) device technology has dominated electronics for the last 70 years. CMOS has been able to scale down at an incredible pace, predicted by the famed Moore's law. However, it appears that further scaling of CMOS devices may encounter a road block by the end of the decade due to various issues, primarily among which is the rapid increase in heat dissipation as more and more devices are packed on to a chip with increasing densities.

There is also a strong need for computing devices that can operate with 2–3 orders of magnitude lower energy dissipation than current CMOS devices in embedded applications. Mobile and medical applications would prefer processors that would dissipate so little power that they can be run on energy harvested from the ambient without requiring a separate power source. If this comes to pass, it will open up myriad applications in wearable electronics, medical devices embedded to monitor the health of patients and sensor networks that monitor critical infrastructure such as buildings and bridges.

For these reasons, several new device concepts have been advanced as potential replacements for CMOS devices, or to complement CMOS devices for specific applications such as nonvolatile memory and logic, or to implement certain functionalities such as neuromorphic computing in a way better than CMOS devices can. They draw upon different physical mechanisms to elicit computational or signal processing activity. Among these different physical paradigms, spintronic and nanomagnetic devices form an important class both for the rich variety of physical phenomena on which these devices are based and the many different device concepts that they have spawned.

The editors hope that this book will provide the reader with a broad understanding of the key concepts behind spintronic and nanomagnetic devices as well as summarize the latest developments in this field. Questions and comments can be addressed to J. Atulasimha (jatulasimha@vcu.edu) and S. Bandyopadhyay (sbandy@vcu.edu).