Handbook of Spintronics

Yongbing Xu • David D. Awschalom
Junsaku Nitta
Editors

Handbook of Spintronics

With 807 Figures and 36 Tables

Springer Reference

Editors
Yongbing Xu
York-Nanjing International Center of
Spintronics, Nanjing University
Nanjing, China

Spintronics and Nanodevice Laboratory
The University of York
York, UK

Junsaku Nitta
Department of Materials Science
Graduate School of Engineering
Tohoku University
Sendai, Japan

David D. Awschalom
Institute for Molecular Engineering
University of Chicago
Chicago, IL, USA

ISBN 978-94-007-6891-8 ISBN 978-94-007-6892-5 (eBook)
ISBN 978-94-007-6893-2 (print and electronic bundle)
DOI 10.1007/978-94-007-6892-5

Library of Congress Control Number: 2015947249

Springer Dordrecht Heidelberg New York London

Printed on acid-free paper

Springer Science+Business Media B.V. Dordrecht is part of Springer Science+Business Media (www.springer.com)

Preface

The IT industry has followed Moore's Law for decades, successfully predicting the number of transistors on a chip doubles about every 2 years, and has changed almost every aspect of our life. To keep electronics development at the pace of the Moore's Law, revolutionary technologies are needed. Spintronics is a promising area of science and technology that may impact both near- and long-term electronics. While conventional semiconductor devices rely on the electron charge and the magnetic data storage media on electron spin, spintronics exploits both charge and spin to achieve new functionality. Many spintronic devices are non-volatile, fast and energy efficient, and are likely to impact many industries including mass data storage, micro/nano electronics and bio-medical sensors. The Magnetic RAM (MRAM), for example, may combine the functions of both DRAM and SRAM.

Spintronics is a multidisciplinary and fast growing research area. The research is closely related to physics, chemistry, materials science, device fabrication, electrical engineering, and computer science and system integration. The discovery of Giant Magnetoresistance (GMR) in the magnetic metallic multilayers in the early eighties initiated metallic spintronic research. The following research into Tunnelling Magnetoresistance (TMR) effect in metallic/oxide spin valves has led to the development of MRAM. The research of diluted magnetic semiconductors and hybrid structures is leading the way of developing a spin-FET, capable of both data storage and processing. Recent exciting research into coherent spin manipulation in graphene, diamond, topological insulators and other 2D materials will speed up the development of quantum information processing and new generation of quantum spintronics, beyond our imagination.

This "Handbook of Spintronics" seeks to cover many important aspects of spintronics research with contributions from world leading scientists in these areas. We are grateful to all the authors, our associate editors and all the member

of the advisory board for their time and contributions. We would also like to thank Tom Spicer, Abhijit Baroi and the publication team of Springer for their great efforts in publishing this book.

York, UK — Yongbing Xu
Sendai, Japan — David D. Awschalom
Chicago, IL, USA — Junsaku Nitta
June 2015

Contents

Volume 1

Volume 2

About the Editors

Yongbing Xu
York-Nanjing International Center of
Spintronics, Nanjing University
Nanjing, China
and
Spintronics and Nanodevice Laboratory
The University of York
York, UK

Yongbing Xu Chair Professor in Nanotechnology, heads the Spintronics and Nanodevice Laboratory of the University of York. He is the codirector of the York–Nanjing Joint Centre for Spintronics and Nano Engineering and Qianren Concurrent Professor of Nanjing University and guest professor of several other Chinese universities. He was awarded a Ph.D. by Nanjing University in 1990 and then by Leeds University in 1992. He was a senior research fellow in Cavendish Laboratory, University of Cambridge, since 1996 and then moved to York to establish and lead the York Spintronics and Nanodevice Laboratory in 2001. He was the cofounder of the York Nanocentre and the founder and the head of the York Nanotechnology B.Eng./M.Eng. Programme. Over the past 30 years, his research has been focused on the fabrication and characterization of a wide variety of spintronics materials and devices, supported by the EPSRC, EU-FP7, CNSF, STFC, the Royal Society, the Yorkshire Forward, the White Rose Consortium, WUN, etc. He was winner of the EPSRC Advanced Fellowship award in 2000 in the area of spintronics and the VC's outstanding achievement award in 2011 by the University of York. He is the chair of the Worldwide University Network (WUN) Spintronics Consortium with partners from 12 leading UK, US, and Chinese research universities. He was the spintronics section editor of *Current Opinion in Solid State and Materials Science* by Elsevier, the series editor of *Electronic Materials and Devices* by Taylor and Francis/CRC Press, and edited the book *Spintronic Materials and Technology* by CRC Press. He has served the NSF panel, the international advisory committee of the EU Warsaw NanoCenter, the panel of "The Technology and Innovation Future 2020" of the UK Government Science Office, and many research councils around the world.

David D. Awschalom
Institute for Molecular Engineering
University of Chicago
Chicago, IL, USA

David D. Awschalom Professor Awschalom received his B.Sc. in physics from the University of Illinois at Urbana-Champaign, and his Ph.D. in experimental physics from Cornell University. He was a Research Staff member and Manager of the Nonequilibrium Physics Department at the IBM Watson Research Center in Yorktown Heights, New York. In 1991 he joined the University of California-Santa Barbara as a Professor of Physics, and was appointed as a Professor of Electrical and Computer Engineering. During that period he served as the Peter J. Clarke Professor and Director of the California NanoSystems Institute, and Director of the Center for Spintronics and Quantum Computation. Professor Awschalom is currently the Liew Family Professor in Spintronics and Quantum Information within the Institute for Molecular Engineering at the University of Chicago.

His research in quantum spintronics involves understanding and controlling the spin of electrons and nuclei for fundamental studies of matter at the atomic scale, advanced computing, molecular imaging, and nanometer-scale sensing technologies. His group has research activities in optical and magnetic interactions in semiconductor quantum structures, spin dynamics and coherence in condensed matter systems, macroscopic quantum phenomena in nanometer-scale magnets, and implementations of quantum information processing in the solid state. He has developed a variety of femtosecond-resolved spatiotemporal spectroscopies and micromagnetic sensing techniques aimed at exploring charge and spin motion in the quantum domain.

Professor Awschalom received an IBM Outstanding Innovation Award, the Outstanding Investigator Prize from the Materials Research Society, the International Magnetism Prize and Néel Medal from the International Union of Pure and Applied Physics, the Oliver E. Buckley Prize from the American Physical Society, the Agilent Europhysics Prize from the European Physical Society, the Newcomb Cleveland Prize from the American Association for the Advancement of Science, the UC Faculty Research Lecturer Award, the David Turnbull Award from the Materials Research Society, and the Julius Edgar Lilienfeld Prize from the American Physical Society. Professor Awschalom is a Fellow of the American Physical Society and the American Association for the Advancement of Science. He is a member of the American Academy of Arts and Sciences, the National Academy of Sciences, the National Academy of Engineering, and the European Academy of Sciences.

Junsaku Nitta
Department of Materials Science
Graduate School of Engineering
Tohoku University
Sendai, Japan

Junsaku Nitta joined NTT as a research scientist after graduation from the Department of Electrical Engineering, Kyushu University, in 1981. He received his Ph.D. from Kyushu University in 1990 because of his work on Control of Quantum Flux Propagation in Josephson Transmission Line. He stayed in Groningen University, The Netherlands, as a visiting researcher for 1 year in 1994–1995. He was a group leader of spintronics in NTT Basic Research Laboratories in 2001–2005. Since 2005, Dr. Nitta is a professor in the Department of Materials Science, Graduate School of Engineering, Tohoku University. He is an Editor of *Physica E: Low dimensional Systems and Nanostructures* since 2008.

Associate Editors

Stuart S. P. Parkin IBM-Stanford Spintronic Science and Applications Center (SpinAps), IBM Almaden Research Center, San Jose, CA, USA

Nitin Samarth Department of Physics, Pennsylvania State University, University Park, PA, USA

Rong Zhang School of Electronics Science and Engineering, Nanjing University, Nanjing, China

Editorial Advisory Board

Contributors

Hiroto Adachi Advanced Science Research Center (ASRC), Japan Atomic Energy Agency (JAEA), Tokai, Japan

CREST, Japan Science and Technology Agency, Tokyo, Japan

Juan G. Alzate Department of Electrical Engineering, University of California, Los Angeles, CA, USA

Pedram Khalili Amiri Department of Electrical Engineering, University of California, Los Angeles, CA, USA

A. Anane Unité Mixte de Physique CNRS/Thales, Palaiseau, France

Université Paris Sud, Orsay, France

Kazuya Ando Department of Applied Physics and Physico-Informatics, Keio University, Yokohama, Japan

C. T. Au Chemistry Department, Hong Kong Baptist University, Hong Kong, People's Republic of China

Sébastien Bandiera Crocus Technology, Grenoble, France

Supriyo Bandyopadhyay Department of Electrical and Computer Engineering, Virginia Commonwealth University, Richmond, VA, USA

Jack Bass Department of Physics and Astronomy, 4220 Biomedical Physical Sciences, Michigan State University, East Lansing, MI, USA

Behtash Behin-Aein School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN, USA

Global Foundries, Milpitas, CA, USA

O. Boulle Laboratoire SpinTec, CEA, Grenoble, France

Jens Brede Institute of Applied Physics and Interdisciplinary Nanoscience Center Hamburg, University of Hamburg, Hamburg, Germany

Chris Bunce Physics Department, University of York, York, UK

Daniel E. Bürgler Peter Grünberg Institute, Electronic Properties (PGI-6), Forschungszentrum Jülich GmbH, Jülich, Germany

Guido Burkard Department of Physics, University of Konstanz, Konstanz, Germany

William Butler MINT Center, University of Alabama, Tuscaloosa, AL, USA

Marc Cahay Department of Electrical and Computer Engineering, School of Electronics and Computing Systems, University of Cincinnati, Cincinnati, OH, USA

Lin Chen State Key Laboratory of Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China

Tuyuan Cheng Physics Department, University of York, York, UK

Bruno Chilian Institute of Applied Physics and Interdisciplinary Nanoscience Center Hamburg, University of Hamburg, Hamburg, Germany

A. V. Chumak Fachbereich Physik and Forschungszentrum OPTIMAS, Technische Universität Kaiserslautern, Kaiserslautern, Germany

Supriyo Datta School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN, USA

Bernard Dieny SPINTEC UMR8191 (CEA/CNRS/Grenoble Alpes Univ.), Grenoble, France

Vinh Diep School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN, USA

John F. DiTusa Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA, USA

B. Dlubak Unité Mixte de Physique CNRS/Thales, Palaiseau, France

Université Paris Sud, Orsay, France

Jun Du National Laboratory of Solid State Microstructures, Nanjing University, Nanjing, China

Y. W. Du Nanjing National Laboratory of Microstructures, Nanjing University, Nanjing, People's Republic of China

S. Esefelder Leibniz Institute of Photonic Technology, Jena, Germany

Claudia Felser Institute for Analytical and Inorganic Chemistry, Johannes Gutenberg-University, Mainz, Germany

Albert Fert Unité Mixte de Physique CNRS/Thales, Palaiseau, France

Université Paris Sud, Orsay, France

Michael Foerster Institute of Physics, Johannes Gutenberg-University Mainz, Mainz, Germany

Shinobu Fujita Toshiba Corporate R & D Center, Kawasaki, Japan

Tanja Graf Institute for Analytical and Inorganic Chemistry, Johannes Gutenberg-University, Mainz, Germany

IBM Almaden Research Center, San Jose, CA, USA

Max-Planck-Institut für Chemical Physics of Solids, Dresden, Germany

Peter Grünberg Peter Grünberg Institute, Electronic Properties (PGI-6), Forschungszentrum Jülich GmbH, Jülich, Germany

Xiu-Feng Han Chinese Academy of Sciences, State Key Laboratory of Magnetism, Institute of Physics, Beijing, China

Sameh Hassan York Laboratory of Spintronics and Nanodevices, Department of Electronics, The University of York, York, UK

Burkard Hillebrands Fachbereich Physik, Technische Universität Kaiserslautern, Kaiserslautern, Germany

Nguyen Hoa Hong Department of Physics and Astronomy, Seoul National University, Seoul, South Korea

Hiroshi Idzuchi Center for Emergent Matter Science, RIKEN, 2-1 Hirosawa, Wako, Japan

H. Jaffres Unité Mixte de Physique CNRS/Thales, Palaiseau, France

Université Paris Sud, Orsay, France

B. T. Jonker Naval Research Laboratory, Washington, DC, USA

T. Jungwirth Institute of Physics ASCR, v.v.i., Praha 6, Czech Republic

School of Physics and Astronomy, University of Nottingham, Nottingham, UK

Alexy D. Karenowska Department of Physics and Magdalen College, University of Oxford, Oxford, UK

Alexander Ako Khajetoorians Institute of Applied Physics and Interdisciplinary Nanoscience Center Hamburg, University of Hamburg, Hamburg, Germany

Takashi Kimura Department of Physics, Inamori Frontier Research Center, Kyushu University, Fukuoka, Japan

G. Kioseoglou Naval Research Laboratory, Washington, DC, USA

Department of Materials Science and Technology, University of Crete, Heraklion Crete, Greece

Mathias Kläui Institute of Physics, Johannes Gutenberg-University Mainz, Mainz, Germany

Kazuyuki Koike Department of Condensed Matter of Physics, Graduate School of Science, Hokkaido University, Sapporo, Japan

Xufeng Kou Engineering Electrical Department, University of California, Los Angeles, CA, USA

Murong Lang Engineering Electrical Department, University of California, Los Angeles, CA, USA

C. H. Li Naval Research Laboratory, Washington, DC, USA

Wenqing Liu York Laboratory of Spintronics and Nanodevices, Department of Electronics, The University of York, York, UK

Cong Lu Electronics Department, University of York, York, UK

Xianyang Lu Physics Department, University of York, York, UK

Yongxiong Lu York Laboratory of Spintronics and Nanodevices, Department of Electronics, The University of York, York, UK

Stefan Maat HGST, a Western Digital Company, San Jose, CA, USA

Sadamichi Maekawa Advanced Science Research Center (ASRC), Japan Atomic Energy Agency (JAEA), Tokai, Japan

CREST, Japan Science and Technology Agency, Tokyo, Japan

Arley C. Marley Magnetic Recording Heads Development, HGST, a Western Digital Company, San Jose, CA, USA

M.-B. Martin Unité Mixte de Physique CNRS/Thales, Palaiseau, France

Université Paris Sud, Orsay, France

R. Mattheis Leibniz Institute of Photonic Technology, Jena, Germany

Daxin Niu York Laboratory of Spintronics and Nanodevices, Department of Electronics, The University of York, York, UK

Y. Otani Center for Emergent Matter Science, RIKEN, 2-1 Hirosawa, Wako, Japan

Institute for Solid State Physics, University of Tokyo, Kashiwa, Japan

Stuart S. P. Parkin IBM-Stanford Spintronic Science and Applications Center (SpinAps), IBM Almaden Research Center, San Jose, CA, USA

Min Ren School of Chemistry and Chemical Engineering, Nanjing University, Nanjing, People's Republic of China

Eiji Saitoh Institute for Materials Research, Tohoku University, Sendai, Japan

Angik Sarkar School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN, USA

Elaine A. Seddon The Photon Science Institute, The University of Manchester, Manchester, UK

The Cockcroft Institute, Sci-Tech Daresbury, Daresbury, Warrington, UK

P. Seneor Unité Mixte de Physique CNRS/Thales, Palaiseau, France

Université Paris Sud, Orsay, France

A. A. Serga Fachbereich Physik and Forschungszentrum OPTIMAS, Technische Universität Kaiserslautern, Kaiserslautern, Germany

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

Srikant Srinivasan School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN, USA

Iowa State University, Ames, IA, USA

Philipp R. Struck Department of Physics, University of Konstanz, Konstanz, Germany

Satoshi Sugahara Department of Electronics and Applied Physics, Tokyo Instituteof Technology, Tokyo, Japan

Hao-Ling Sun Department of Chemistry, Beijing Normal University, Beijing, People's Republic of China

Jonathan Z. Sun IBM Research, Yorktown Heights, NY, USA

Li Sun Department of Mechanical Engineering and Texas Center for Superconductivity (TcSUH), University of Houston, Houston, TX, USA

Saburo Takahashi Institute for Materials Research, Tohoku University, Sendai, Japan

Yota Takamura Dept. of Physical Electronics, Tokyo Institute of Technology, Meguro-ku, Tokyo, Japan

Jinkui Tang State Key Laboratory of Rare Earth Resource Utilization, Changchun Institute of Applied Chemistry, Chinese Academy of Sciences, Changchun, People's Republic of China

Brian K. Tanner Department of Physics, Durham University, Durham, UK

Sebastiaan van Dijken NanoSpin, Department of Applied Physics, Aalto University, School of Science, Aalto, Finland

Gerrit van der Laan Magnetic Spectroscopy Group, Diamond Light Source, Didcot, UK

Kang L. Wang Department of Electrical Engineering, University of California, Los Angeles, CA, USA

Jill Weaver York Laboratory of Spintronics and Nanodevices, Department of Electronics, The University of York, York, UK

Jens Wiebe Institute of Applied Physics and Interdisciplinary Nanoscience Center Hamburg, University of Hamburg, Hamburg, Germany

Roland Wiesendanger Institute of Applied Physics and Interdisciplinary Nanoscience Center Hamburg, University of Hamburg, Hamburg, Germany

Iain Will York Laboratory of Spintronics and Nanodevices, Department of Electronics, The University of York, York, UK

Johnny Wong York Laboratory of Spintronics and Nanodevices, Department of Electronics, The University of York, York, UK

Jing Wu Physics Department, University of York, York, UK

Yongbing Xu York-Nanjing International Center of Spintronics, Nanjing University, Nanjing, China

Spintronics and Nanodevice Laboratory, The University of York, York, UK

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

Yu Yan York Laboratory of Spintronics and Nanodevices, Department of Electronics, The University of York, York, UK

X. J. Yao Nanjing National Laboratory of Microstructures, Nanjing University, Nanjing, People's Republic of China

Hiroaki Yoda Toshiba Electronics Korea Corporation, Seoul, Republic of Korea

Wen Zhang York Laboratory of Spintronics and Nanodevices, Department of Electronics, The University of York, York, UK

Xiaoguang Zhang Department of Physics and Quantum Theory Project, University of Florida, Gainesville, FL, USA

Computer Science and Mathematics Division and Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, Oak Ridge, TN, USA

Jianhua Zhao State Key Laboratory of Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China

Li-Min Zheng School of Chemistry and Chemical Engineering, Nanjing University, Nanjing, People's Republic of China

W. Zhong Nanjing National Laboratory of Microstructures, Nanjing University, Nanjing, People's Republic of China

Shiming Zhou School of Physics Science and Engineering, Tongji University, Shanghai, China

Xiao Zhou Physics Department, University of York, York, UK