

# **Nanoscale Magnetic Materials and Applications**

J. Ping Liu  
Eric Fullerton  
Oliver Gutfleisch  
David J. Sellmyer  
Editors

# Nanoscale Magnetic Materials and Applications

Foreword by Peter Grünberg

 Springer

*Editors*

J. Ping Liu  
University of Texas, Arlington  
Department of Physics  
502 Yates Street  
Arlington, TX 76019  
USA  
pliu@uta.edu

Eric Fullerton  
University of California, San Diego  
Center for Magnetic Recording Research  
9500 Gilman Drive  
La Jolla, CA 92093-0401  
USA  
efullerton@ucsd.edu

Oliver Gutfleisch  
Leibniz Institute for Solid State  
and Materials Research  
(IFW Dresden)  
Institute of Metallic Materials  
Helmholtzstr. 20  
D-01069 Dresden  
Germany  
o.gutfleisch@ifw-dresden.de

David J. Sellmyer  
Department of Physics and Astronomy  
and Nebraska Center for Materials  
and Nanoscience  
University of Nebraska  
Lincoln, NE 68588-0113  
USA  
dsellmyer@unl.edu

ISBN 978-0-387-85598-1 e-ISBN 978-0-387-85600-1

DOI 10.1007/978-0-387-85600-1

Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2008943510

© Springer Science+Business Media, LLC 2009

All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden.

The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

Printed on acid-free paper

Springer is part of Springer Science+Business Media ([www.springer.com](http://www.springer.com))

# Foreword

The appearance of materials with dimensions on the nanoscale has brought new stimulus also to magnetism. The discoveries of giant magnetoresistance and tunnel magnetoresistance can be seen as a result of this development.

Generally, magnetism tends to become weaker or even disappears when the geometrical dimensions of samples are decreased. In thin films used for data storage in magnetic recording, for example, this can lead to instability of stored information.

However, this trend is not always to the disadvantage of possible applications. In small nanoscale particles, for example, the occurrence of superparamagnetism leads to hysteresis-free magnetization curves with vanishing remanence. This is useful when the magnetic response should be given as much as possible by an external field rather than by the “magnetic history” of the material. There are numerous examples for this in medical applications as described in this volume. On the other hand – to dwell a little further on the mentioned problem in data storage – new interactions have also been discovered, which are operative on the nanoscale and can be used to solve a given problem. Such an interaction is the interlayer exchange coupling, which is employed in antiferromagnetically coupled (AFC) media to enhance the stability of stored information.

Magnetic surfaces and interfaces represent further special classes of nanoscale materials. Uncompensated spins at the surface of an antiferromagnet, for instance, give rise to a phenomenon called “exchange bias”, which is applied in magnetic field sensors to tailor the response curve.

For magnetic structures on the nanoscale there is also a new possibility to affect their magnetic order by means of electrical currents. This phenomenon called “current-induced magnetization dynamics” is foreseen to be used for writing information. It is currently one of the most active fields of research on nanoscale magnetism and also offers a new method of microwave generation by the current-driven precession of the magnetization.

Hence, a variety of new phenomena operative on the nanoscale is available to render nanomagnetism an interesting research field and to generate the potential for new applications. What are the systems, in which these phenomena can occur? We mentioned already layered magnetic structures and nanoparticles. Other classes of materials are magnetic nanowires and dots, either lithographically defined or

realized by assembling molecules and atoms such as fullerenes filled with magnetic materials.

The field of nanomagnetism is rich indeed both from a fundamental scientific viewpoint and with respect to applications and new devices.

Peter Grünberg  
2007 Nobel Prize in Physics

# Preface

This book has its genesis in the 2007 Materials Research Society (MRS) Fall Meeting where we organized the symposium “Nanoscale Magnetic Materials and Applications”. This symposium, with more than 200 submissions of presentations and 30 invited talks, was one of the most successful meetings in magnetic materials research in recent years. Ms. Elaine Tham from Springer suggested us to edit a book based on the topics presented in this symposium. We invited a number of presenters in the symposium to be the authors of this book which shares the title of the symposium. Moreover, we have extended the scope of the book to other topics as well that were not covered in the symposium.

Magnetic materials have a long history. People have been using compasses for thousands of years. However, new magnetic materials and applications are emerging and are proving indispensable in our daily lives and modern industries. One example is that there are already over a billion giant magnetoresistance sensors produced for information technology and other related applications. Hard and soft magnetic materials are key for efficient energy conversion, especially for converting electric energy to mechanical energy so that they are important to meet the challenges of the depletion of fossil fuels, climate change, and global warming.

Nanotechnology is one of the most important developments in science and technology in our generation, and it has brought revolutionary progress in materials processing and characterization. Current magnetic nanotechnologies have their roots in the development of bulk materials, such as permanent magnets where the functionality is derived from a complex nanoscale multi-phase morphology. Nanotechnology has offered a coupling of synthesis, theory, and characterization of materials at the nanoscale that enables materials design to evolve beyond earlier Edisonian approaches. By its very nature, magnetic materials are a class of nanoscale materials. Although early researchers did not explicitly work on the nanoscale, theoretical research revealed some time ago that nanoscale correlations exist in magnetic materials and control their properties. Several important characteristic dimensions in magnetism are in the nanoscale range such as the magnetic domain wall thickness and the “exchange length” in hard magnetic phases. This highlights why the research and development of new nanoscale magnetic materials are important and will lead to enhanced performance and new functionality. Some recent examples highlighted in this book include patterned magnetic recording

media and exchange-coupled nanocomposite magnets, where intense worldwide efforts are underway to significantly improve the areal density of data storage and the energy product of permanent magnets, respectively.

This book covers many of the exciting areas in nanoscale magnetic materials and applications. Readers will find topics in the book including theoretical work on novel magnetic structures, characterization of magnetic structures, single-phase materials and nanocomposite magnets, spintronic materials, domain structure and domain wall motion, magnetic nanoparticles and patterned magnetic recording media, magnetocaloric effect, and shape memory effect. The book also covers the most important emerging applications of advanced materials. The applications include new devices based on domain wall motion driven by current or fields, new magnetic sensors based on giant magnetoresistance and tunneling magnetoresistance, soft and hard magnetic materials for specific applications, thin-film applications in micro-electro-mechanical systems, and nanoparticle applications in biomedicine. We hope that this new book provides a comprehensive view of recent progress in all the related fields.

While attempting to present the most exciting developments in materials research and device applications, discussions in depth about the novel phenomena and emerging new materials are also presented in the book, such as the controllable exchange bias and inter-phase exchange interactions. Though more work is needed to understand the issues, we hope that this book gives a good introduction to future advancement.

We thank Prof. Peter Grünberg, the 2007 Nobel Laureate in Physics, for giving his insightful and visionary foreword to this book. We thank Ms. Elaine Tham and Ms. Lauren Danahy from Springer who initiated this book and did a great deal of work to bring it to completion. Mrs. Grace Liu has worked hard in collecting all the manuscripts, figures, and related paperwork. Finally, we thank all of our authors who contributed their very informative and in-depth chapters which made this new book a reality.

Arlington, TX, USA  
La Jolla, CA, USA  
Dresden, Germany  
Lincoln, NE, USA

J. Ping Liu  
Eric Fullerton  
Oliver Gutfleisch  
David J. Sellmyer

# Contents

<b>1 Spin Dynamics: Fast Switching of Macro-spins . . . . .</b>	<b>1</b>
X.R. Wang, Z.Z. Sun, and J. Lu	
1.1 Introduction . . . . .	1
1.2 Spin and Its Kinetics and Dynamics . . . . .	3
1.2.1 Basic Concepts of Spin . . . . .	3
1.2.2 Kinetics of Spin: Spin Current . . . . .	4
1.2.3 Dynamics of Spin: Bloch Equation, Landau–Lifshitz Equation, and Landau– Lifshitz–Gilbert Equation . . . . .	5
1.3 Macro-spin Reversal with a Static Magnetic Field . . . . .	9
1.3.1 A Nonlinear Dynamics Picture of Magnetization Reversal . . . . .	9
1.3.2 The Exactness of SW-Limit at Infinitely Large Dissipation . . . . .	11
1.3.3 Critical Value of Damping Constant . . . . .	13
1.3.4 Ballistic Reversal . . . . .	15
1.4 Macro-spin Reversal with a Time-Dependent Magnetic Field . . . . .	17
1.4.1 Strategy I: Field Following the Magnetization Motion . . . . .	18
1.4.2 Strategy II: Synchronizing the Magnetization Motion with a Circularly Polarized Microwave . . . . .	21
1.4.3 Theoretical Limits of Switching Field/Current and Optimal Reversal Pulses . . . . .	25
1.5 Summary . . . . .	32
References . . . . .	32
<b>2 Core–Shell Magnetic Nanoclusters . . . . .</b>	<b>35</b>
Jinlan Wang and X.C. Zeng	
2.1 Introduction . . . . .	35
2.2 Experimental Studies of Core–Shell Magnetic Clusters . . . . .	37
2.2.1 Iron-Based (Fe@Au) Core–Shell Nanoclusters . . . . .	38
2.2.2 Cobalt-Based Core–Shell Nanoclusters . . . . .	44
2.2.3 Ni-Based Core–Shell Nanoclusters . . . . .	50



2.3	Theoretical Studies of Bimetallic Magnetic Core–Shell Nanoclusters . . . . .	51
2.3.1	Iron-Based (Fe@Au) Core–Shell Nanoclusters . . . . .	51
2.3.2	Cobalt-Based Core–Shell Nanoclusters . . . . .	53
2.3.3	Mn-Based Core–Shell Nanoclusters: [Mn <sub>13</sub> @Au <sub>20</sub> ] <sup>−</sup> . . . . .	59
2.4	Summary . . . . .	60
	References . . . . .	62
<b>3</b>	<b>Designed Magnetic Nanostructures . . . . .</b>	<b>67</b>
	A. Enders, R. Skomski, and D.J. Sellmyer	
3.1	Introduction . . . . .	67
3.2	Structure, Chemistry, and Geometry . . . . .	70
3.2.1	Synthesis of Supported Nanostructures . . . . .	71
3.2.2	Case Study: Fe Clusters on Pt Surfaces . . . . .	73
3.2.3	Structure of Embedded Clusters . . . . .	75
3.2.4	Case Study: FePt Clusters in a Carbon Matrix . . . . .	78
3.3	Anisotropy and Hysteresis . . . . .	79
3.3.1	Surface and Interface Anisotropies . . . . .	80
3.3.2	Hysteresis of Fe Clusters on Pt . . . . .	81
3.3.3	Role of Heavy Transition Metals . . . . .	83
3.3.4	Proteresis . . . . .	85
3.4	Quantum-Mechanical Effects . . . . .	86
3.4.1	Embedding from a Quantum-Mechanical Point of View . . . . .	86
3.4.2	Exchange Interactions . . . . .	87
3.4.3	Preasymptotic Coupling . . . . .	90
3.4.4	Kondo Effect . . . . .	92
3.4.5	Entanglement . . . . .	93
3.5	Concluding Remarks . . . . .	95
	References . . . . .	95
<b>4</b>	<b>Superconductivity and Magnetism in Silicon and Germanium Clathrates . . . . .</b>	<b>105</b>
	Joseph H. Ross Jr. and Yang Li	
4.1	Introduction . . . . .	106
4.2	Superconductivity in Si <sub>46</sub> Clathrates . . . . .	108
4.3	Rattler Atoms and Narrow Bands . . . . .	109
4.4	Superconducting Mechanism . . . . .	111
4.5	Zintl Concept and Vacancies . . . . .	115
4.6	Superconductivity in Other Clathrates . . . . .	117
4.7	Magnetism . . . . .	117
4.8	Conclusions . . . . .	119
	References . . . . .	119

<b>5</b>	<b>Neutron Scattering of Magnetic Materials</b>	123
	Olivier Isnard	
5.1	Introduction	123
5.2	Interaction of Neutrons and Materials: A Brief Presentation	124
5.3	Crystal Structure Investigation	126
5.3.1	Powder Diffraction	126
5.3.2	Single Crystal Diffraction	126
5.4	In Situ Neutron Diffraction	128
5.4.1	Thermodiffraction: Crystallization of Amorphous Materials	128
5.4.2	In Situ Investigation of the Synthesis and Ordering of nanocrystalline FePt Alloys	129
5.4.3	Time-Resolved Neutron Diffraction Studies	130
5.5	Magnetic Structure Determination	133
5.6	Magnetic Phase Transition	135
5.6.1	Magnetic Phase Transitions Studied by Powder Diffraction	135
5.6.2	Magnetic Phase Transitions Studied by Single Crystal Diffraction	137
5.7	Polarized Neutron Techniques	138
5.7.1	Uniaxial Polarization Analysis	138
5.7.2	Spherical Neutron Polarimetry	141
5.8	Small-Angle Neutron Scattering	141
5.9	Neutron Scattering on Magnetic Surfaces	144
5.10	Magnetic Excitations	146
5.11	Neutron Scattering Under Extreme Conditions	148
5.12	Conclusions	150
	References	150
<b>6</b>	<b>Tunable Exchange Bias Effects</b>	159
	Ch. Binek	
6.1	Introduction	160
6.2	Electrically Tuned Exchange Bias	165
6.2.1	Electrically Tuned Exchange Bias with Magnetoelectrics	165
6.2.2	Electrically Tuned Exchange Bias with Multiferroics	168
6.2.3	Piezomagnetically and Piezoelectrically Tuned Exchange Bias	169
6.3	Magnetic Field Control of Exchange Bias	170
6.4	Training Effect in Exchange-Coupled Bilayers	174
6.4.1	Physical Background of Training Effects in Various Systems	174

6.4.2	Tuning the Training Effect . . . . .	178
6.5	Conclusion . . . . .	179
	References . . . . .	179
<b>7</b>	<b>Dynamics of Domain Wall Motion in Wires with Perpendicular Anisotropy . . . . .</b>	<b>185</b>
	Dafiné Ravelosona	
7.1	Introduction . . . . .	185
7.2	Basics of Field-Induced DW Motion in Pt/Co/Pt Ultra-Thin Films . . . . .	187
7.2.1	Mechanisms of Magnetization Reversal in Pt/Co/Pt Trilayers . . . . .	188
7.2.2	Different Regimes of DW Motion: The Role of Defects . . . . .	189
7.3	Control and Detection of Single DW Motion in Magnetic Wires . . . . .	192
7.3.1	Wires Nanofabrication and Injection of a Single Domain Wall . . . . .	193
7.3.2	Electrical Methods to Detect DW Motion Along Tracks . . . . .	194
7.4	Field-Induced DW Motion Along Wires: Role of Structural Defects . . . . .	196
7.4.1	The Role of Edge Roughness on the Creep Regime in Co/Pt Films . . . . .	196
7.4.2	The Role of Intrinsic Defects in Co/Ni Films . . . . .	201
7.5	Control of the Pinning Potential . . . . .	203
7.5.1	Ion Irradiation of Co/Pt Films: A Way to Reduce Intrinsic Structural Defects . . . . .	204
7.5.2	A DW Propagating in a Hall Cross: An Artificial Pinning Potential . . . . .	207
7.6	Current Induced DW Depinning . . . . .	208
7.7	Conclusion . . . . .	213
	References . . . . .	214
<b>8</b>	<b>Magnetic Nanowires for Domain Wall Logic and Ultrahigh Density Data Storage . . . . .</b>	<b>219</b>
	R.P. Cowburn	
8.1	Domain Wall Propagation and Nucleation . . . . .	219
8.2	Domain Wall Conduits . . . . .	221
8.3	The NOT Gate and Shift Register Element . . . . .	223
8.4	Data Input–Output . . . . .	226
8.5	Using the Chirality of the Transverse Domain Wall . . . . .	228
8.6	Potential Applications of Domain Wall Logic . . . . .	233
8.7	Conclusion . . . . .	234
	References . . . . .	235

<b>9</b>	<b>Bit-Patterned Magnetic Recording: Nanoscale Magnetic Islands for Data Storage</b>	237
	Thomas R. Albrecht, Olav Hellwing, Ricardo Ruiz, Manfred E. Schabes, Bruce D. Terris, and Xiao Z. Wu	
9.1	Introduction	238
9.2	Theoretical Perspective of Bit-Patterned Recording	240
9.2.1	Island Addressability in Bit-Patterned Recording	240
9.2.2	Fabrication Tolerances of BPM	242
9.2.3	Thermal Constraints	243
9.2.4	Magnetostatic Interaction Fields Between Islands	245
9.2.5	BPM Designs for Tb/in <sup>2</sup> Densities	246
9.3	Optimization of the Magnetic Materials	248
9.3.1	Magnetic Characterization	249
9.3.2	Magnetic Switching-Field Distribution	252
9.3.3	Laminated Magnetic Media	254
9.3.4	Magnetic Trench Noise Reduction	255
9.4	Fabrication of Bit-Patterned Media	256
9.5	Generation of Master Patterns Beyond 1Tbit/in <sup>2</sup> via Guided Self-Assembly of Block Copolymer Domain Arrays	259
9.5.1	Ordering, Size Distribution, and Scalability: Patterned Media Requirements vs. Block Copolymer Fundamental Limitations	260
9.5.2	Approaches to Long-Range Orientational and Translational Order in Block Copolymer Templates	262
9.6	Write Synchronization	265
9.6.1	Requirements for Write Synchronization	265
9.6.2	Options to Achieve Write Synchronization	265
9.6.3	Timing Variations Observed in a Conventional Drive	266
9.6.4	Implementation of a Sector Synchronization System	268
9.7	Conclusion	270
	References	271
<b>10</b>	<b>The Magnetic Microstructure of Nanostructured Materials</b>	275
	Rudolf Schäfer	
10.1	Overview	275
10.2	Coarse-Grained Material and Amorphous Ribbons	277
10.3	Domains in Nanocrystalline Ribbons	282
10.3.1	Random Anisotropy Model	283
10.3.2	Interplay of Random and Uniaxial Anisotropies	287
10.3.3	Magnetization Process	292
10.4	Domains in Nanocrystalline Magnetic Films	296

10.5	Domains in Fine- and Nanostructured Permanent Magnets . . .	301
10.6	Summary . . . . .	304
	References . . . . .	304
<b>11</b>	<b>Exchange-Coupled Nanocomposite Permanent Magnets . . . . .</b>	<b>309</b>
	J.P. Liu	
11.1	Introduction . . . . .	309
11.2	Fundamental Aspects . . . . .	311
	11.2.1 The Early Models . . . . .	311
	11.2.2 The Soft Phase Effects . . . . .	313
	11.2.3 The Interface Effects . . . . .	314
	11.2.4 Coercivity Mechanisms . . . . .	316
	11.2.5 Characterization of Inter-phase Exchange Coupling . . . . .	316
11.3	Experimental Approaches . . . . .	321
	11.3.1 The Early Approaches . . . . .	321
	11.3.2 Nanoparticle Approaches . . . . .	322
	11.3.3 Fabrication of Nanocomposite Bulk Magnets . . . . .	327
11.4	Work Toward Anisotropic Nanocomposite Magnets . . . . .	331
	References . . . . .	332
<b>12</b>	<b>High-Temperature Samarium Cobalt Permanent Magnets . . . . .</b>	<b>337</b>
	Oliver Gutfleisch	
12.1	Introduction . . . . .	337
12.2	Physical Metallurgy and Crystal Structures . . . . .	339
12.3	Coercivity Mechanism and the Development of High-Temperature 2:17-Type Magnets . . . . .	343
	12.3.1 The $\text{Sm}(\text{CoCu})_5$ Cell Boundary Phase . . . . .	343
	12.3.2 Alloy Optimization . . . . .	344
	12.3.3 Stability at Operating Temperature . . . . .	348
12.4	Microchemistry and Pinning Behavior in $\text{Sm}_2\text{Co}_{17}$ -Type Magnets . . . . .	349
	12.4.1 Redistribution of Cu and Slow Cooling . . . . .	349
	12.4.2 Stability of Microchemistry . . . . .	352
	12.4.3 “Anomalous” Coercivity Behavior . . . . .	355
12.5	Magnetic Domains and Coercivity . . . . .	357
	12.5.1 Analysis of Magnetic Microstructure . . . . .	357
	12.5.2 Domains and Processing Parameters . . . . .	358
12.6	Non-equilibrium Processing Routes . . . . .	362
	12.6.1 Rapidly Quenched $\text{SmCo}_5/\text{Sm}_2\text{Co}_{17}$ Magnets . . . . .	362
	12.6.2 Mechanically Alloyed $\text{SmCo}_5/\text{Sm}_2\text{Co}_{17}$ Magnets . . . . .	363
	12.6.3 Hydrogen Disproportionated $\text{SmCo}_5$ and $\text{Sm}_2\text{Co}_{17}$ Alloys . . . . .	364
	References . . . . .	367

<b>13 Nanostructured Soft Magnetic Materials</b> . . . . .	373
Matthew A. Willard and Maria Daniil	
13.1 Introduction . . . . .	373
13.2 Materials Development . . . . .	376
13.2.1 Alloy Processing and Design . . . . .	377
13.2.2 Phase Transformations . . . . .	378
13.2.3 Annealing Techniques . . . . .	381
13.3 Magnetic Performance . . . . .	382
13.3.1 Exchange-Averaged Anisotropy . . . . .	383
13.3.2 Intrinsic Magnetic Properties . . . . .	384
13.3.3 Domain Structure . . . . .	385
13.3.4 Hysteretic Losses . . . . .	386
13.3.5 AC Properties . . . . .	388
13.3.6 Thermomagnetism . . . . .	389
13.4 Applications . . . . .	390
13.4.1 Power Applications . . . . .	391
13.4.2 Electromagnetic Interference Applications . . . . .	392
13.4.3 Sensor Applications . . . . .	393
13.5 Summary . . . . .	393
References . . . . .	394
<b>14 Magnetic Shape Memory Phenomena</b> . . . . .	399
Oleg Heczko, Nils Scheerbaum, and Oliver Gutfleisch	
14.1 Introduction . . . . .	399
14.2 Martensitic Transformation and Twinning . . . . .	401
14.3 Modes of Magnetic Field-Induced Strain . . . . .	403
14.3.1 Magnetostriction . . . . .	403
14.3.2 Magnetic Field-Induced Phase Transformation . . . . .	404
14.4 Magnetically Induced Structure Reorientation . . . . .	405
14.5 The Ni–Mn–Ga System . . . . .	408
14.5.1 Compositional Dependence of Structure and Transformation . . . . .	408
14.5.2 Martensitic Phases in Ni–Mn–Ga . . . . .	410
14.5.3 Magnetic Properties of Ni–Mn–Ga . . . . .	412
14.6 Twin Boundary Mobility . . . . .	416
14.7 Energy Model for MIR . . . . .	418
14.8 Angular Dependence . . . . .	421
14.9 Reversible and Irreversible MIR Strain . . . . .	422
14.10 Temperature Dependence of MIR . . . . .	426
14.11 MIR in Polycrystals, Composites, and Films . . . . .	427
14.12 Other Applications Based on MSM Alloys . . . . .	430
14.13 Conclusion . . . . .	430
Further Reading . . . . .	431
References . . . . .	431

<b>15 Magnetocaloric Effect and Materials</b> . . . . .	441
J.R. Sun, B.G. Shen, and F.X. Hu	
15.1 Introduction . . . . .	441
15.2 Theoretical Description of Magnetocaloric Effect . . . . .	443
15.3 Experimental Determination of Magnetocaloric Effect . . . . .	446
15.3.1 Direct Measurement of Adiabatic Temperature Change . . . . .	446
15.3.2 Indirect Measurement of Entropy and Adiabatic Temperature Changes . . . . .	446
15.4 Magnetocaloric Effect Associated with First-Order Phase Transition . . . . .	447
15.4.1 MCE Due to an Idealized First-Order Transition . . . . .	447
15.4.2 MCE Due to a Non-Idealized First-Order Phase Transition . . . . .	448
15.5 Typical Materials with Giant Magnetocaloric Effect . . . . .	451
15.5.1 $\text{LaFe}_{3-x}\text{M}_x$ ( $\text{M} = \text{Al}, \text{Si}$ ) Intermetallics . . . . .	452
15.5.2 $\text{Gd}_5(\text{Ge},\text{Si})_4$ and Related Compounds . . . . .	472
15.5.3 Mn-Based Heusler Alloys . . . . .	476
15.5.4 Mn–As-Based Compounds . . . . .	478
15.6 Concluding Remarks . . . . .	479
References . . . . .	479
<b>16 Spintronics and Novel Magnetic Materials for Advanced Spintronics</b> . . . . .	485
Jiwei Lu, Kevin G. West, Jiani Yu, Wenjing Yin, David M. Kirkwood, Li He, Robert Hull, Stuart A. Wolf, and Daryl M. Treger	
16.1 Introduction to Spintronics . . . . .	485
16.2 Novel Magnetic Oxide Thin Films by Reactive Bias Target Ion Beam Deposition . . . . .	489
16.2.1 Reactive Bias Target Ion Beam Deposition (RBTIBD) . . . . .	490
16.2.2 $\text{Cr}_x\text{V}_{1-x}\text{O}_2$ Thin Films . . . . .	491
16.2.3 $\text{Co}_x\text{Ti}_{1-x}\text{O}_2$ Thin Films . . . . .	496
16.3 Diluted Ferromagnetic $\text{Ge}_{1-x}\text{Mn}_x$ by Ion Implantation . . . . .	500
Additional Reading on Spintronics . . . . .	507
References . . . . .	507
<b>17 Growth and Properties of Epitaxial Chromium Dioxide (<math>\text{CrO}_2</math>) Thin Films and Heterostructures</b> . . . . .	511
Guo-Xing Miao and Arunava Gupta	
17.1 Density of States (DOS) of Half-Metallic $\text{CrO}_2$ and the Double Exchange Mechanism . . . . .	511
17.2 Intrinsic Properties of Epitaxial $\text{CrO}_2$ Films . . . . .	513

17.3	Influence of Strain on the Magnetic Properties of CrO <sub>2</sub> Thin Films . . . . .	517
17.3.1	Film Growth on Atomically Smooth TiO <sub>2</sub> Substrates . . . . .	517
17.3.2	Films Grown on As-Polished TiO <sub>2</sub> Substrates . . . . .	521
17.4	CrO <sub>2</sub> -Based Heterostructures . . . . .	523
17.4.1	Epitaxial SnO <sub>2</sub> Barrier Layer . . . . .	525
17.4.2	Epitaxial RuO <sub>2</sub> Barrier Layer . . . . .	528
17.4.3	VO <sub>2</sub> Barrier Layer . . . . .	530
17.4.4	TiO <sub>2</sub> Barrier Layer . . . . .	531
17.4.5	Cr <sub>2</sub> O <sub>3</sub> Barrier Layer . . . . .	532
	References . . . . .	535
<b>18</b>	<b>FePt and Related Nanoparticles . . . . .</b>	<b>537</b>
	J.W. Harrell, Shishou Kang, David E. Nikles, Gregory B. Thompson, Shifan Shi, and Chandan Srivastava	
18.1	Introduction . . . . .	538
18.2	Thermal Effects in Magnetic Nanoparticles . . . . .	538
18.3	Magnetic Recording and the Superparamagnetic Limit . . . . .	541
18.4	Chemical Synthesis and Shape Control of FePt and Related Nanoparticles . . . . .	541
18.4.1	Synthesis . . . . .	541
18.4.2	Shape Control . . . . .	544
18.5	Prevention of Sintered Grain Growth During Annealing . . . . .	545
18.5.1	FePt/MnO Core/Shell Nanoparticles . . . . .	546
18.5.2	FePt/SiO <sub>2</sub> Core/Shell Nanoparticles . . . . .	547
18.5.3	Salt Matrix Annealing . . . . .	548
18.5.4	Flash Annealing . . . . .	549
18.6	Effect of Metal Additives on Chemical Ordering and Sintered Grain Growth . . . . .	550
18.7	Easy-Axis Orientation . . . . .	552
18.7.1	Model of Easy-Axis Orientation . . . . .	552
18.7.2	Easy-Axis Orientation Measurements . . . . .	553
18.8	Composition Distribution . . . . .	554
18.9	Anisotropy Distribution . . . . .	556
18.10	Size Effect on Chemical Ordering . . . . .	556
18.11	Summary and Conclusions . . . . .	557
	References . . . . .	558
<b>19</b>	<b>Magnetic Manipulation of Colloidal Particles . . . . .</b>	<b>563</b>
	Randall M. Erb and Benjamin B. Yellen	
19.1	Introduction . . . . .	563
19.2	Magnetic Manipulation of Particles . . . . .	565
19.2.1	Deterministic and Brownian-Dominated Particle Systems . . . . .	565
19.2.2	Material Properties . . . . .	565



19.2.3	Magnetic Force . . . . .	568
19.3	Deterministic Particle Manipulation . . . . .	570
19.3.1	Substrate-Based Self-Assembly of Particles . . . . .	570
19.3.2	Substrate-Based Transport and Separation . . . . .	571
19.4	Brownian-Influenced Particle Manipulation . . . . .	573
19.4.1	Magnetic and Nonmagnetic Particle Chains . . . . .	573
19.4.2	Magnetic and Nonmagnetic Mixed Assemblies in Ferrofluid . . . . .	576
19.4.3	Anisotropic Particle Alignment . . . . .	576
19.5	Brownian-Dominated Manipulation of Particle Populations . . . . .	579
19.5.1	Modeling Thermal Diffusion . . . . .	579
19.5.2	Magnetic Particle Concentration . . . . .	581
19.5.3	Nonmagnetic Particle Concentrations . . . . .	584
19.5.4	Applications of Concentration Gradients . . . . .	586
19.6	Conclusions and Outlook . . . . .	587
	References . . . . .	588
<b>20</b>	<b>Applications of Magnetic Nanoparticles in Biomedicine</b> . . . . .	<b>591</b>
	Carlos Bárcena, Amandeep K. Sra, and Jinming Gao	
20.1	Introduction . . . . .	591
20.2	Nanoparticle Classification . . . . .	592
20.3	Syntheses of SPIO Nanoparticles . . . . .	593
20.3.1	Co-precipitation . . . . .	593
20.3.2	Microemulsion . . . . .	594
20.3.3	Thermal Decomposition . . . . .	595
20.3.4	Alternative Methods . . . . .	596
20.4	Surface Modifications of Magnetic Nanoparticles . . . . .	596
20.4.1	Organic and Polymeric Stabilizers . . . . .	597
20.4.2	Inorganic Molecules . . . . .	598
20.5	Pharmacokinetics and Toxicology . . . . .	600
20.6	Biomedical Applications of Magnetic Nanoparticles . . . . .	603
20.6.1	Magnetic Resonance Imaging . . . . .	603
20.6.2	Therapeutic Applications . . . . .	612
20.7	Conclusion . . . . .	616
	Abbreviations . . . . .	616
	References . . . . .	618
<b>21</b>	<b>Nano-Magnetophotonics</b> . . . . .	<b>627</b>
	Mitsuteru Inoue, Alexander Khanikaev, and Alexander Baryshev	
21.1	Introduction . . . . .	627
21.2	Magnetophotonic Crystals . . . . .	628
21.2.1	1D MPCs Composed of Alternating Magnetic and Dielectric Layers . . . . .	629
21.2.2	Microcavity-Type 1D MPCs . . . . .	633
21.2.3	Photonic Band Structure and Eigenmodes of 2D MPCs . . . . .	635

21.2.4	Faraday Rotation of Three-Dimensional Magnetophotonic Crystals . . . . .	637
21.2.5	Nonlinear Optical and Magneto-Optical Properties . . . . .	640
21.2.6	Conclusion . . . . .	641
21.3	Magnetorefractive Effect in Nanostructures . . . . .	641
21.3.1	Magnetorefractive Effect in Nanostructures and Manganites . . . . .	642
21.3.2	Enhancement of the MRE in Magnetophotonic Crystals . . . . .	644
21.3.3	Conclusion . . . . .	647
21.4	Plasmon-Enhanced Magneto-Optical Responses . . . . .	647
21.4.1	Garnet–Noble Metal Nanocomposites . . . . .	648
21.4.2	Metal–Garnet Structures Supporting Transmission Resonances . . . . .	651
21.4.3	Conclusion . . . . .	653
	References . . . . .	653
<b>22</b>	<b>Hard Magnetic Materials for MEMS Applications . . . . .</b>	<b>661</b>
	Nora M. Dempsey	
22.1	An Introduction to MEMS . . . . .	661
22.1.1	What Are MEMS? . . . . .	661
22.1.2	How Are MEMS Made? . . . . .	662
22.2	Magnetic MEMS . . . . .	662
22.2.1	Downscaling Magnetic Systems . . . . .	663
22.2.2	Prototype Magnetic MEMS . . . . .	665
22.3	Permanent Magnets . . . . .	666
22.4	Fabrication of $\mu$ -Magnets: Top-Down Routes . . . . .	667
22.4.1	Bulk Processed Magnets . . . . .	668
22.4.2	Bulk Processed Hard Magnetic Powders . . . . .	669
22.5	Fabrication of Thick Hard Magnetic Films . . . . .	671
22.5.1	Electrodeposition . . . . .	672
22.5.2	Sputtering . . . . .	672
22.5.3	Pulsed Laser Deposition (PLD) . . . . .	675
22.6	Micro-Patterning of Thick Hard Magnetic Films . . . . .	676
22.6.1	Topographically Patterned Films . . . . .	676
22.6.2	Crystallographically Patterned Films . . . . .	679
22.7	Conclusions and Perspectives . . . . .	680
	References . . . . .	680
<b>23</b>	<b>Solid-State Magnetic Sensors for Bioapplications . . . . .</b>	<b>685</b>
	Goran Mihajlović and Stephan von Molnár	
23.1	Introduction . . . . .	685
23.2	Magnetic Sensors Based on GMR Effect . . . . .	687
23.2.1	GMR Sensors . . . . .	689
23.2.2	Spin Valve Sensors . . . . .	693

23.2.3	GMR and Spin Valve Sensors for Detection of Nanoparticles . . . . .	695
23.3	MTJ Sensors . . . . .	697
23.4	Sensors Based on AMR Effect . . . . .	700
23.4.1	AMR Ring Sensors . . . . .	700
23.4.2	Planar Hall Effect Sensors . . . . .	700
23.5	Hall Effect Sensors . . . . .	702
23.6	GMI Sensors . . . . .	706
23.7	Conclusions . . . . .	707
	References . . . . .	708
<b>Index</b>	. . . . .	<b>711</b>

# Contributors

**Thomas R. Albrecht** Hitachi Global Storage Technologies, San Jose Research Center, San Jose, CA 95123, USA, Thomas.Albrecht@hitachigst.com

**Carlos Bárcena** Harold C. Simmons Comprehensive Cancer Center, University of Texas Southwestern Medical Center at Dallas, Dallas, TX 75390; Department of Chemistry, University of Texas at Dallas, Richardson, TX 75080, USA

**Alexander Baryshev** Toyohashi University of Technology, Toyohashi, Aichi, Japan; Ioffe Physico-Technical Institute, 194021 St. Petersburg, Russia

**Ch. Binek** Department of Physics and Astronomy, Nebraska Center for Materials and Nanoscience, University of Nebraska, Lincoln, NE 68588, USA, cbinek2@unlnotes.unl.edu

**R.P. Cowburn** Blackett Physics Laboratory, Imperial College London, Prince Consort Road, London SW7 2BW, UK, r.cowburn@imperial.ac.uk

**Maria Daniil** US Naval Research Laboratory, Washington, DC, USA

**Nora M. Dempsey** Institut Néel, CNRS-UJF, 25 rue des Martyrs, 38042, Grenoble, France, nora.dempsey@grenoble.cnrs.fr

**A. Enders** Department of Physics and Astronomy and Nebraska Center for Materials and Nanoscience, University of Nebraska, Lincoln, NE 68508, USA, axel@unl.edu

**Randall M. Erb** Department of Mechanical Engineering and Materials Science, Center for Biologically Inspired Materials and Material Systems, Duke University, Durham, NC 27708, USA, randall.erb@duke.edu

**Jinming Gao** Harold C. Simmons Comprehensive Cancer Center, University of Texas Southwestern Medical Center at Dallas, Dallas, TX 75390; Department of Chemistry, University of Texas at Dallas, Richardson, TX 75080, USA, Jinming.Gao@UTSouthwestern.edu

**Arunava Gupta** Center for Materials for Information Technology (MINT), The University of Alabama, Tuscaloosa, AL 35487, USA, agupta@mint.ua.edu

**Oliver Gutfleisch** Leibniz Institute for Solid State and Materials Research (IFW Dresden), Institute for Metallic Materials, Helmholtzstr. 20, 01069 Dresden, Germany, o.gutfleisch@ifw-dresden.de

**J.W. Harrell** Department of Physics, Center for Materials for Information Technology, The University of Alabama, Tuscaloosa, AL 35487-0209, USA, jharrell@bama.ua.edu

**Li He** Department of Materials Science and Engineering, University of Virginia, Charlottesville, VA, 22904, USA

**Oleg Heczko** Leibniz Institute for Solid State and Materials Research (IFW Dresden), Institute for Metallic Materials, Helmholtzstr. 20, 01069 Dresden, Germany, Institute of Physics, Academy of Sciences, Czech Republic Na Slovance 2, CZ-182 21 Praha 8, Czech Rep., heczko@fzu.cz

**Olav Hellwig** Hitachi Global Storage Technologies, San Jose Research Center, San Jose, CA 95123, USA

**F.X. Hu** State Key Laboratory for Magnetism, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, Peoples' Republic of China

**Robert Hull** Department of Materials Science and Engineering, University of Virginia, Charlottesville, VA, 22904, USA

**Mitsuteru Inoue** Toyohashi University of Technology, Toyohashi, Aichi, Japan, inoue\_mitsuteru@eee.tut.ac.jp

**Olivier Isnard** Institut Néel, CNRS, Boîte F, BP166, F-38042 Grenoble, Cédex 9, France, olivier.isnard@grenoble.cnrs.fr

**Shishou Kang** Center for Materials for Information Technology, The University of Alabama, Tuscaloosa, Alabama 35487-0209, USA, skang@mint.ua.edu

**Alexander Khanikaev** Toyohashi University of Technology, Toyohashi, Aichi, Japan

**David M. Kirkwood** Department of Materials Science and Engineering, University of Virginia, Charlottesville, VA, 22904, USA

**Yang Li** Department of Engineering Science and Materials, University of Puerto Rico at Mayaguez, Mayaguez, PR 00681-9044

**J.P. Liu** Department of Physics, University of Texas at Arlington, Arlington, TX 76019, USA, pliu@uta.edu

**Jiwei Lu** Department of Materials Science and Engineering, University of Virginia, Charlottesville, VA, 22904, USA

**J. Lu** Physics Department, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong SAR, China

**Guo-Xing Miao** Center for Materials for Information Technology (MINT), The University of Alabama, Tuscaloosa, AL 35487, USA

**Goran Mihajlović** Materials Science Division, Argonne National Laboratory, Argonne, IL 60439, mihajlovic@anl.gov

**David E. Nikles** Department of Chemistry, Center for Materials for Information Technology, The University of Alabama, Tuscaloosa, Alabama 35487-0209, USA, dnikles@mint.ua.edu

**Dafiné Ravelosona** Institut d'Electronique Fondamentale, UMR CNRS 8622, Université Paris Sud, 91405 Orsay, France, dafine.ravelosona@u-psud.fr

**Joseph H. Ross, Jr** Department of Physics, Texas A&M University, College Station, TX 77843-4242, USA, ross@physics.tamu.edu

**Ricardo Ruiz** Hitachi Global Storage Technologies, San Jose Research Center, San Jose, CA 95123, USA

**Manfred E. Schabes** Hitachi Global Storage Technologies, San Jose Research Center, San Jose, CA 95123, USA

**Rudolf Schäfer** Leibniz Institute for Solid State and Materials Research (IFW Dresden), Institute for Metallic Materials, Helmholtzstr. 20, 01069 Dresden, Germany, r.schaefer@ifw-dresden.de

**Nils Scheerbaum** Leibniz Institute for Solid State and Materials Research (IFW Dresden), Institute for Metallic Materials, Helmholtzstr. 20, 01069 Dresden, Germany

**David. J. Sellmyer** Department of Physics and Astronomy and Nebraska Center for Materials and Nanoscience, University of Nebraska, Lincoln, NE 68508, USA

**B.G. Shen** State Key Laboratory for Magnetism, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, Peoples' Republic of China

**Shifan Shi** Department of Physics, Center for Materials for Information Technology, The University of Alabama, Tuscaloosa, Alabama 35487-0209, USA, shi004@bama.ua.edu

**R. Skomski** Department of Physics and Astronomy and Nebraska Center for Materials and Nanoscience, University of Nebraska, Lincoln, NE 68508, USA, rskomski@neb.rr.com

**Amandeep K. Sra** Harold C. Simmons Comprehensive Cancer Center, University of Texas Southwestern Medical Center at Dallas, Dallas, TX 75390, USA

**Chandan Srivastava** Department of Metallurgical and Materials Engineering, Center for Materials for Information Technology, The University of Alabama, Tuscaloosa, Alabama 35487-0209, USA, sriva001@bama.ua.edu

**Z.Z. Sun** Physics Department, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong SAR, China

**J.R. Sun** State Key Laboratory for Magnetism, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, Peoples' Republic of China, jrsun@g203.iphy.ac.cn

**Bruce D. Terris** Hitachi Global Storage Technologies, San Jose Research Center, San Jose, CA 95123, USA

**Gregory B. Thompson** Department of Metallurgical and Materials Engineering, Center for Materials for Information Technology, The University of Alabama, Tuscaloosa, Alabama 35487-0209, USA, gthompson@coe.eng.ua.edu

**Daryl M. Treger** Strategic Analysis, Arlington, VA 22203, USA

**Stephan von Molnár** MARTECH and Department of Physics, Florida State University, Tallahassee, FL 32306, USA

**Jinlan Wang** Department of Physics, Southeast University, Nanjing, 211189, P. R. China

**X.R. Wang** Physics Department, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong SAR, China, phxwan@ust.hk

**Kevin G. West** Department of Materials Science and Engineering, University of Virginia, Charlottesville, VA, 22904, USA

**Matthew A. Willard** US Naval Research Laboratory, Washington, DC, USA, willard@anvil.nrl.navy.mil

**Stuart A. Wolf** Department of Materials Science and Engineering, University of Virginia, Charlottesville, VA, 22904, USA, saw6b@Virginia.EDU

**Xiao Z. Wu** Hitachi Global Storage Technologies, San Jose Research Center, San Jose, CA 95123, USA

**Benjamin B. Yellen** Department of Mechanical Engineering and Materials Science, Center for Biologically Inspired Materials and Material Systems, Duke University, Durham, NC 27708, USA, yellen@duke.edu

**Wenjing Yin** Department of Materials Science and Engineering, University of Virginia, Charlottesville, VA, 22904, USA

**Jiani Yu** Department of Materials Science and Engineering, University of Virginia, Charlottesville, VA, 22904, USA

**X.C. Zeng** Department of Chemistry and Nebraska Center for Materials and Nanoscience, University of Nebraska, Lincoln, Nebraska 68588, USA, xzengl@unl.edu

# Chapter 1

## Spin Dynamics: Fast Switching of Macro-spins

X.R. Wang, Z.Z. Sun, and J. Lu

**Abstract** Recent progress on the theoretical studies of fast magnetization reversal of Stoner particles is reviewed. The following results are discussed: (1) The Stoner–Wohlfarth (SW) limit becomes exact when the damping constant is infinitely large. Under the limit, magnetization moves along the steepest energy descent path. (2) For a given magnetic anisotropy, there is a critical damping constant, above which the minimal switching field is the same as that of the SW-limit. (3) The field of a ballistic magnetization reversal should be along a certain direction window in the presence of energy dissipation. (4) Since a time-dependent magnetic field can be an energy source, two new reversal strategies are possible. One is to use a field following magnetization motion, and the other is to use a circularly polarized microwave near the ferromagnetic resonance frequency. The critical switching fields of both strategies are substantially lower than that of precessional reversal for realistic materials. (5) The theoretical limits for both field-induced and current-induced magnetization reversal are presented for uniaxial Stoner particles.

### 1.1 Introduction

Spin dynamics is an old and important subject rooted in magnetism and the nuclear/electron-spin/ferromagnetic resonances that have wide applications in physics, information processing, chemistry, biology, and medicine [1–5]. In the field of magnetic data storage [4], magnetization reversal has received a lot of attention because data input and output involve switching the magnetization of magnetic storage cells that are important components of modern computers. The typical switching time with currently used technology is of the order of nanoseconds. If one wants to have a faster computer (modern electronic computers are working at a clock speed

---

X.R.Wang (✉)  
Physics Department, The Hong Kong University of Science and Technology, Clear Water Bay,  
Hong Kong SAR, China  
e-mail: phxwan@ust.hk



of the order of GHz) with magnetic random access memory (MRAM), the conventional magnetization reversal method shall be a bottleneck. Thus, fast magnetization switching shall be of great importance for future development of high-speed information industry.

Magnetization reversal is a very complicated problem in bulk material [5] because it can be achieved in many different ways. For example, magnetization reversal can go through bucking and curling modes, coherent rotation, and/or domain nucleation and domain wall propagation. Recent technological advances allow us to fabricate magnetic nano-particles [6] that are believed to be useful for high-density information storage [7–10]. For a magnetic nano-particle, strong exchange interactions keep the magnetic moments of atoms rigid, creating just a single magnetic domain, such that the constituent spins rotate in unison. Such a nano-particle is often called a Stoner–Wohlfarth (SW) or Stoner particle. The understanding of magnetization reversal of a Stoner particle should be relatively simple in comparison with that of a bulk system, yet important in nano-technologies [4] as a consequence of the miniaturization into the nano-meter scale.

Magnetization reversal of macro-spins (of Stoner particles) is known as the SW problem because it was first studied by Stoner and Wohlfarth in 1948 [11]. One current topic in nanomagnetism is the control and manipulation of the magnetization of Stoner particles, and magnetization reversal is one of the basic operations. Magnetization state can be manipulated by a magnetic field [11–22], or by a spin-polarized electric current [23–28] through so-called spin-transfer torque (STT), or by a laser light [30]. In terms of applications, manipulation by a magnetic field and/or a spin-polarized electric current dominates and will continue to dominate the information storage industry. Examples are field-driven and current-driven MRAM. Important issues in applications are scalability, power consumption, and speed. These issues relate to the problems of lowering the critical field/current required to reverse a magnetization [4], as well as to the problems of designing a field/current pulse such that the magnetization can be switched from one state to another extremely quickly [21, 29].

Regarding the issue of minimal switching field, Stoner and Wohlfarth [11] showed that a static field larger than the so-called SW-limit can switch a magnetization from its initial state to the target one. The idea is to make the target state to be the only energy minimum. Thus the system rolls down to the target state. However, the system can only gradually dissipate its energy during a precessional motion so that the magnetization moves around the precession axis many times (ringing phenomenon or ringing mode) [12–16, 21, 22] before reaching the target state. As a result, it takes typically nanoseconds to switch a magnetization at a field of teslas. Subsequent theoretical and experimental studies [14, 15] have shown that the minimal switching field can be smaller than the SW-limit. The energy consideration alone in the SW theory is not adequate, and one has to take into account magnetization dynamics. The magnetization dynamics of a nano-structure is governed by the so-called Landau–Lifshitz–Gilbert (LLG) equation that does not have a general analytical solution. Most theoretical work in the field has relied on numerical calculations, and most reversal schemes [21, 27, 28] have

been proposed on a hunch. Ideas include thermal assistance [27] and sample designs [28].

Regarding the issue of switching time, picoseconds magnetization switching has been observed recently in experiments [14, 15] by using pulsed magnetic fields. This approach has received much theoretical attention [12, 17–19]. Numerical investigations [12] showed that the switching time can be substantially reduced because ringing effect is avoided so that the magnetization moves along a so-called ballistic trajectory [19]. The precessional magnetization reversal provides not only a shorter time but also a lower switching field (well below the SW-limit), as found in the early numerical calculations [12]. In the absence of energy dissipation, precessional magnetization switching can also be investigated analytically. Analytical results for the minimal field were obtained by Porter [20].

There are already many nice reviews and books on the general subject of spin dynamics, and we shall not try to make a thorough review on the subject. Instead, we concentrate on the recent theoretical progress on two issues of the SW problem. One is how to make magnetization reversal fast, and the other is how to lower the switching field/current. For those readers who want to know more about many other aspects of spin dynamics, they may read several nice books [1–4] on the subject. The outline of this chapter is as follows. A brief introduction of spin and its kinetics and dynamics subjected to different interactions are given in Section 1.2. These include the dynamics of an isolated spin (without damping) and the dynamics of a macro-spin in contact with the environments (with damping through spin relaxation and spin decoherence). Spin current as a result of spin kinetics is also discussed. Section 1.3 is about magnetization reversal by a static magnetic field. The existence of a critical damping constant, above which the SW theory predicts correctly the switching field, is discussed, and a direction window for ballistic reversal is explained. Section 1.4 is about the macro-spin reversal by a time-dependent magnetic field. The fundamental difference between a static magnetic field and a time-dependent magnetic field is revealed. Based on the fact that a time-dependent magnetic field can be an energy source, two strategies with substantial lower (than the precessional one) critical switching field are discussed. The theoretical limits of the critical switching field or current out of all possible designs, together with the optimal reversal trajectory, are also given. Section 1.5 is a short summary.

## 1.2 Spin and Its Kinetics and Dynamics

### 1.2.1 Basic Concepts of Spin

Like electric charge, spin and the associated magnetic moment are fundamental properties (intrinsic quantum numbers) of elementary particles. The spin quantum number relates to many phenomena in elementary particle physics as well as in nuclear, atomic, solid state, and statistical physics. Spin is one type of angular momentum which does not have a classical analogy, but one may tentatively view

a spin coming from a spinning motion of a particle. From the symmetry transformation viewpoint, spin is one class of generators of spatial rotation transformations, while electric charge is the generator of so-called U(1) gauge symmetry transformations. Spin has three components,  $s_1$ ,  $s_2$ , and  $s_3$  that generate rotations around x-, y-, and z-axis. Unlike electric charge being a scalar, the expectation value of a spin operator  $\vec{s}$  is a vector. According to quantum mechanics, spin operators  $\vec{s}$  satisfies the following fundamental commutation relations

$$[s_j, s_k] = i\hbar\varepsilon_{jkl}s_l, \quad (1.1)$$

where  $\varepsilon_{jkl}$  is an antisymmetric tensor on three indices, for which  $\varepsilon_{jkl} = 0$  except for  $\varepsilon_{123} = \varepsilon_{231} = \varepsilon_{312} = 1$  and  $\varepsilon_{321} = \varepsilon_{213} = \varepsilon_{132} = -1$ . This symmetry viewpoint explains well why spin is a good quantum number of an elementary particle that has an intrinsic rotational symmetry. From quantum mechanics, it is known that a spin can take only integers or half-integers values of  $\hbar$ .

Following classical electrodynamics, the magnetic moment of a charged particle moving in a circular orbit is given by

$$\vec{M} = \frac{q}{2m_e}\vec{L}, \quad \vec{L} = \vec{r} \times \vec{p}, \quad (1.2)$$

where  $q$  and  $m_e$  are the charge and the mass of the particle, respectively.  $\vec{L}$  is the orbital angular momentum of a particle at position  $\vec{r}$  with momentum  $\vec{p}$ . Although the magnetic moments of elementary particles and their spins do not follow exactly the above equation, they are related to each other by

$$\vec{M} = g\frac{q}{2m_e}\vec{s} \quad (1.3)$$

with  $g$  a fundamental parameter for a given particle.

### 1.2.2 Kinetics of Spin: Spin Current

Just as the flow of charge generates electric current, so the flow of spin in space creates a spin current. Different from the electric current density which is a vector, spin current density is a rank-2 tensor because of the vector nature of spin. As mentioned earlier, spin is only one type of angular momenta. All particles can have orbital angular momentums besides spins. An electron can exchange its spin with its orbital angular momentum through spin-orbit interaction or exchange its spin angular momentum with the angular momenta of other electrons and/or particles through particle-particle interactions. As a result, spin current is very fragile, not continuous, and does not even conserve because the spin state of an electron is seldom stationary. To see why the spin current behaves like this, it may be helpful to understand why an electric current reaches easily the continuity condition. The

reason is not only due to the charge conservation (otherwise, the spin current should also be very robust) but also because of both charge quantization and large Coulomb interaction. Each type of particle carries only a fixed number of charges. For example, all electrons have one negative charge. Large Coulomb interaction prevents any real material from either absorbing or releasing excessive charges. In comparison, an electron can be in any innumerable number of possible spin states, and there is no interaction to prevent angular momentum accumulation and transformation from one object to another.

The differences in the electric current and spin current make the study of spin current much more challenging than that of electric current. In fact, even the issue of a proper definition of the spin current has been an active issue of debate recently in the spintronics community [31–33]. Interested readers are referred to the literature [31–33] for a full discussion.

### 1.2.3 Dynamics of Spin: Bloch Equation, Landau–Lifshitz Equation, and Landau–Lifshitz–Gilbert Equation

Consider a spin  $\vec{s}$  under the influence of its Hamiltonian  $W(\vec{s})$ . The dynamics of  $\vec{s}$  is governed by the Heisenberg equation if  $\vec{s}$  can be regarded as a closed system

$$\frac{d\vec{s}}{dt} = \frac{1}{i\hbar} [\vec{s}, W(\vec{s})]. \quad (1.4)$$

It is straightforward to evaluate the commutator, and Eq. (1.4) becomes

$$\frac{d\vec{s}}{dt} = \gamma \vec{s} \times \vec{H}_t, \quad (1.5)$$

where  $\gamma = 2.21 \times 10^5 (\text{rad/s})/(\text{A/m})$  is the gyromagnetic ratio, and the effective field  $\vec{H}_t = -\nabla_{\vec{s}} W(\vec{s})/\gamma$  comes from external magnetic fields and from various magnetic anisotropy energies [5]. If one takes the expectation value of the above equation with respect to the spin state, and assumes  $\langle -\gamma \vec{s} \times \vec{H}_t \rangle = -\gamma \langle \vec{s} \rangle \times \langle \vec{H}_t \rangle$ , then the magnetization of an isolated spin,  $\vec{M} \equiv \gamma \langle \vec{s} \rangle$ , satisfies the following dynamic equation

$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}_t. \quad (1.6)$$

Classically,  $\vec{H}_t = -\nabla_{\vec{M}} W(\vec{M})/\mu_0$ , where  $\mu_0 = 4\pi \times 10^{-7} \text{N/A}^2$  is the vacuum magnetic permeability, and  $W(\vec{M})$  is the classical magnetic energy density.

### 1.2.3.1 Bloch Equation

Equation (1.6) is called the Bloch equation of an isolated spin by the nuclear magnetic resonance (NMR) and quantum optics scientific community because of the critical contributions of F. Bloch on these subjects. It is also known as the Landau–Lifshitz equation without dissipation in magnetism. Equation (1.6) is correct only for isolated spins, which is not the case for most realistic systems. Spins in a sample made up by condensed matter experience various interactions with other dynamical degree of freedoms of the sample and its environment. These interactions create internal magnetic fields. Due to the dynamical nature of the environments, these internal fields not only contribute an averaged field to the total magnetic field  $\vec{H}_t$  but also exert residual fluctuating fields on the spins. These fluctuating fields, originated in the infinite number of degrees of freedom of the environment as well as their thermal and the quantum fluctuations, can lead to both spin relaxation and spin decoherence, meaning that the spin magnetization will approach to a preferred equilibrium value  $M_{z0}$  along the z-axis which is selected by either external magnetic field or sample anisotropy. The physics is as what was explicitly demonstrated in Reference [34]: A random field perpendicular to the z-axis, which produces an off-diagonal term in the Hamiltonian, can induce transitions between different spin states. The randomness in the transitions and the spontaneous decay of quantum fluctuations leads the spin magnetization to take an equilibrium statistical value. The fluctuating field along the z-direction makes the spin precession random, which gives rise to spin decoherence.

If one takes into account spin relaxation and spin decoherence in the spin dynamics, the proper way to describe the magnetization dynamics is the so-called Bloch equation with spin relaxation and spin decoherence.

$$\begin{aligned}
 \frac{dM_z}{dt} &= -\gamma(M_x H_{ty} - M_y H_{tx}) - \frac{M_z - M_{z0}}{T_1} \\
 \frac{dM_x}{dt} &= -\gamma(M_y H_{tz} - M_z H_{ty}) - \frac{M_x}{T_2} \\
 \frac{dM_y}{dt} &= -\gamma(M_z H_{tx} - M_x H_{tz}) - \frac{M_y}{T_2}
 \end{aligned} \tag{1.7}$$

where  $T_1$  and  $T_2$  are called spin relaxation time and spin decoherence time, respectively.  $T_1$  is the typical time for an initial non-equilibrium  $M_z$  to reach the equilibrium value  $M_{z0}$ , and  $T_2$  is the typical time for a magnetization to lose the memory of its initial precession position. The above equation is the starting point of usual NMR analysis because the NMR signal is related to the average magnetization  $\vec{M}$  of an ensemble of spins.

### 1.2.3.2 Landau–Lifshitz Equation and Landau–Lifshitz–Gilbert Equation

The Bloch equation describes well the magnetization dynamics of an ensemble of non-interacting or weakly interacting spins, but it does not capture the proper

physics of a strongly interacting spin system such as a piece of magnet. This is because the magnetization magnitude of a magnet shall not change with time, and Eq. (1.7) does not preserve the magnitude of the magnetization. To take into account the dissipative effect of the environment, Landau and Lifshitz [35] introduced a phenomenological term,  $\alpha\gamma\vec{m} \times (\vec{M} \times \vec{H}_t)$ , where  $\alpha$  is a dimensionless phenomenological parameter measuring the damping strength, and  $\vec{m}$  is the unit vector of  $\vec{M}$ . Equation (1.6) with this damping term becomes

$$\frac{d\vec{M}}{dt} = -\gamma\vec{M} \times \vec{H}_t - \alpha\gamma\vec{m} \times (\vec{M} \times \vec{H}_t). \quad (1.8)$$

Equation (1.8) is called the Landau–Lifshitz (LL) equation.

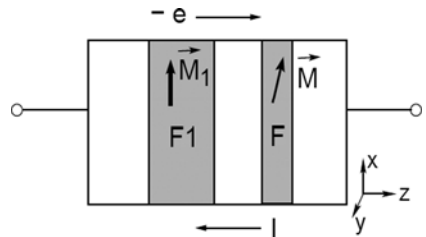
Later Gilbert [36] proposed an alternative way to include dissipation. Similar to Ohm’s law in electron transport, Gilbert assumed a friction field of  $-\alpha(d\vec{m}/dt)$  on a moving magnetization due to the dissipation. This friction field generates a torque on the magnetization. Thus Eq. (1.6) should be modified as

$$\frac{d\vec{M}}{dt} = -\gamma\vec{M} \times \vec{H}_t + \alpha\vec{M} \times \frac{d\vec{m}}{dt}. \quad (1.9)$$

This equation is called the Landau–Lifshitz–Gilbert (LLG) equation that can also be written as

$$(1 + \alpha^2)\frac{d\vec{M}}{dt} = -\gamma\vec{M} \times \vec{H}_t - \alpha\gamma\vec{m} \times (\vec{M} \times \vec{H}_t). \quad (1.10)$$

Although Eqs. (1.10) and (1.8) have the same mathematical form, the two approaches to the dissipation are fundamentally different. According to Eq. (1.10), the change rate of the magnetization goes to zero as  $\alpha \rightarrow \infty$ , and the magnetization shall move along the dissipation direction of  $-\vec{m} \times (\vec{M} \times \vec{H}_t)$  when  $\alpha \rightarrow \infty$ . However, Eq. (1.8) says that the rate change of the magnetization becomes infinity at infinite damping, and it does not make any sense. Thus LL’s approach to dissipation is not physical! It is generally accepted that LLG equation is the right description of magnetization dynamics for a magnet, and it is the starting point in our discussion of magnetization reversal of Stoner particles.



**Fig. 1.1** An STT structure. Note that the direction of the electrical current is opposite to that of electron flow