Magnetic Memory

If you are a semiconductor engineer or a magnetics physicist developing magnetic memory, get the information you need with this, the first book on magnetic memory.

From magnetics to the engineering design of memory, this practical book explains key magnetic properties and how they are related to memory performance, characterization methods of magnetic films, and tunneling magnetoresistance effect devices. It also covers memory cell options, array architecture, circuit models, and read-write engineering issues.

You'll understand the soft-fail nature of magnetic memory, which is very different from that of semiconductor memory, as well as methods to deal with the issue. You'll also get invaluable problem-solving insights from real-world memory case studies.

This is an essential book, both for semiconductor engineers who need to understand magnetics, and for magnetics physicists who work with MRAM. It is also a valuable reference for graduate students working in electronic/magnetic device research.

Denny D. Tang is Vice President of MagIC Technologies, Inc., and has over 30 years' experience in the semiconductor industry. After receiving his Ph.D. in Electrical Engineering from the University of Michigan in 1975, he spent 15 years at IBM T. J. Watson Research Center, Yorktown Heights, NY, 11 years at IBM Almaden Research Center at San José, CA, and 6 years at Taiwan Semiconductor Manufacturing Company (TSMC). He is a Fellow of the IEEE, TSMC, and the Industrial Technology Research Institute (ITRI).

Yuan-Jen Lee is a Senior Engineer at MagIC Technologies, Inc., where he develops advanced magnetic memory technology. He received his Ph.D. from the National Taiwan University in 2003, after which he worked for ITRI, Hsinchu, Taiwan, developing toggle MRAM and spin-torque MRAM.

Magnetic Memory

Fundamentals and Technology

DENNY D. TANG AND YUAN-JEN LEE
MagIC Technologies, Inc.

CAMBRIDGE
UNIVERSITY PRESS

Shaftesbury Road, Cambridge CB2 8EA, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment, a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9780521449649

First published 2010

A catalogue record for this publication is available from the British Library

Library of Congress Cataloging-in-Publication data
Tang, Denny D.
Magnetic memory : fundamentals and technology / Denny D. Tang, Yuan-Jen Lee.
p. cm.
ISBN 978-0-521-44964-9 (Hardback)
1. Magnetic memory (Computers) I. Lee, Yuan-Jen. II. Title.
TK7895.M3T36 2010
621.39′73–dc22

2009051398

ISBN 978-0-521-44964-9 Hardback

Contents

Preface *page* ix
Acknowledgments x

1 Basic electromagnetism 1

1.1 Introduction 1
1.2 Magnetic forces, poles and fields 1
1.3 Magnetic dipoles 2
1.4 Ampère's circuital law 3
1.5 Biot–Savart Law 5
1.6 Magnetic moments 5
1.7 Magnetic dipole energy 6
1.8 Magnetic flux 7
1.9 Magnetic induction 7
1.10 Classical Maxwell equations of electromagnetism 8
1.11 Inductance 9
1.12 Equation tables 10
Homework 11
References 12

2 Magnetic films 13

2.1 Origin of magnetization 13
2.1.1 Russell–Saunders coupling 16
2.1.2 jj coupling 16
2.2 Introduction of magnetic materials 17
2.2.1 Diamagnetism 18
2.2.2 Paramagnetism 20
2.2.3 Ferromagnetism 23
2.2.4 Antiferromagnetism 28
2.2.5 Ferrimagnetism 30
2.3 Ferromagnet/antiferromagnet bilayer structure 30
2.3.1 Intuitive picture in exchange bias 31
2.3.2 Positive exchange bias 33

2.3.3 Theories of exchange bias 35
2.3.4 AFM domain wall model 36
2.3.5 Random field model 38
2.4 Interlayer exchange coupling in ferromagnet/metal/ferromagnet multilayer 39
2.4.1 Ruderman–Kittel–Kasuya–Yosida interaction 41
2.4.2 Néel coupling 44
2.5 Micromagnetic simulation 46
2.5.1 Anisotropy energy 46
2.5.2 Exchange energy 47
2.5.3 Magnetostatic energy 47
2.5.4 Zeeman energy 48
Homework 48
References 49

3 Properties of patterned ferromagnetic films 51

3.1 Introduction 51
3.2 Edge poles and demagnetizing field 51
3.2.1 Demagnetizing factor of elliptic-shaped film 52
3.2.2 Edge curling 54
3.3. Magnetic domain 55
3.3.1 Transition region between domains: domain wall 55
3.3.2 Bloch wall and Néel wall 57
3.3.3 C-state, S-state and vortex 58
3.4 Magnetization behavior under an external field 59
3.4.1 Magnetization rotation in a full film 60
3.4.2 Magnetization rotation in a patterned film 61
3.5 Magnetization switching 62
3.5.1 Magnetization rotation and switching under a field in the easy-axis direction 63
3.5.2 Magnetization rotation and switching under two orthogonal applied fields 64
3.6 Magnetization behavior of a synthetic antiferromagnetic film stack 68
Homework 71
References 72

4 Magnetoresistance effects 74

4.1 Introduction 74
4.2 Anisotropic magnetoresistance 74
4.3 Giant magnetoresistance 77
4.4 Tunneling magnetoresistance 79
4.4.1 Giant tunneling magnetoresistance 83
4.4.2 Tunneling magnetoresistance in perpendicular magnetic tunneling junction 88

Homework 89
References 89

5 Field-write mode MRAMs 91

5.1 Introduction 91
5.2 Magnetic tunnel junction RAM cell 93
5.2.1 Cross-point array 93
5.2.2 1T-1MTJ cell 94
5.3 Read signal 95
5.3.1 Sense reference cell 96
5.3.2 Sense amplifier 98
5.4 Write bit cell with magnetic field 100
5.4.1 Write-field conversion efficiency 100
5.4.2 Write-line cladding 101
5.5 Astroid-mode MRAM 102
5.5.1 Switching-energy barrier of Astroid-mode write 102
5.5.2 Write-error rate of a bit cell 105
5.5.3 Write soft error rate of an array of memory cells 105
Homework 106
5.5.4 Solution to the write disturbance problem 106
5.6 Toggle-mode MRAM 109
5.6.1 Toggle-mode cell 109
5.6.2 Switching of SAF free layer in toggle-mode write 111
5.6.3 Energy diagram of toggle operation 112
5.6.4 Write-current reduction 116
5.7 Characterization method of MRAM chip write performance 116
5.8 Thermally assisted field write 118
5.9 Multi-transistor cells for high-speed MRAM operation 119
References 120

6 Spin-torque-transfer mode MRAM 122

6.1 Introduction 122
6.2 Spin polarization of free electrons in ferromagnets 122
6.3 Interaction between polarized free electrons and magnetization – macroscopic model 124
6.4 Spin-torque transfer in a multilayer thin-film stack 126
6.5 Spin-transfer torque and switching threshold current density 129
6.6 Switching characteristics and threshold in magnetic tunnel junctions 131
6.6.1 Regimes of write pulse width 132
6.6.2 Switching probability in the thermal regime 133
6.6.3 Spin-torque-transfer switching under a magnetic field 140
6.6.4 Magnetic back-hopping 141
6.7 Reliability of tunnel barriers in MTJs 143
6.8 SPICE model of MTJs and memory cells 144

6.9 Memory cell operation 146
6.9.1 *I–V* characteristics of STT memory cell during write 148
6.9.2 Read and write voltage window of STT memory cell 150
6.9.3 Sense signal margin 151
Homework 152
6.9.4 Write-to-breakdown-voltage margin 152
6.10 Data retention and E_b extraction method 153
6.11 Thermal stability of STT memory chip 154
Homework 155
6.12 Write-current reduction 156
6.12.1 Nanocurrent-channel film-stack structure 157
6.12.2 Double-spin-filter structure 159
6.12.3 Perpendicular MTJ 159
6.13 Direct observation of magnetization reversal 161
References 163

7 Applications of MTJ-based technology 165

7.1 Introduction 165
7.2 MRAM market position 165
7.3 MTJ applications in CMOS SoC chips 169
7.3.1 Embedded memory in logic chips 169
7.3.2 Unbalanced MTJ flip-flop 169
7.3.3 Non-volatile multiplexer 172
7.3.4 MTJ data register 172
7.4 System-on-chip power reduction 173
7.5 Runtime reconfigurable electronic system 175
References 175

Appendix A: Unit conversion table for cgs and SI units 176
Appendix B: Dimensions of units of magnetism 177
Appendix C: Physical constants 178
Appendix D: Gaussian distribution and quantile plots 179
Appendix E: Weibull distribution 181
Appendix F: Time-dependent dielectric breakdown (TDDB) of magnetic tunnel junction devices 183
Appendix G: Binomial distribution and Poisson distribution 185
Appendix H: Defect density and the breakdown/TMR distribution of MTJ devices 187
Appendix I: Fe, Ni and Co material parameters 189
Appendix J: Soft error, hard fail and design margin 190

Index 193

Preface

The advent of semiconductor technology has impacted the lives of many of us since the 1970s. Silicon CMOS (complementary metal-oxide-semiconductor) devices are practically ubiquitous, and by the year 2000, the value of the semiconductor industry exceeded that of the automobile industry. The magnetic industry, on the other hand, is much smaller than the semiconductor industry. Engineering schools of universities rarely cover any courses in this discipline. Nonetheless, a tiny magnetic recording device is in the hard disk of every computer. Like CMOS devices, magnetic recording technology is being scaled down from generation to generation. At the time of writing, the physical size of the magnetic bit remains smaller than a DRAM bit on silicon chips.

Researchers working in these two communities had little in common until the development of the modern magnetic random access memory, or MRAM. A MRAM chip is built by integrating magnetic tunneling junction (MTJ) devices onto the silicon CMOS circuits. The research activity of MTJs in academia and industry, both hard disk and semiconductor, has been very active since it first showed signs of technology implication in the mid 1990s. That effort led to the mass production of the MTJ recording head in hard disk in 2006. In the same year, the semiconductor industry announced the first successful introduction of an MTJ memory product. The viability of MTJ technology is proven. It is expected that research activities will develop further, which will increase cooperation between these two research communities. The purpose of this book is to facilitate the dialog and to bridge the gap. Each simple homework problem and answer is designed to help readers to link the magnetics to the memory performance. Thus, the book is suitable for those with discipline of semiconductor devices and wish to expand their knowledge base into the field of magnetic memory, and for those in magnetics who wish to "fine-tune" magnetics for MRAM chips.

The book is organized into seven chapters. Chapter 1 reviews the electric current, as most electrical engineering students learn, in their sophomore and junior years, that magnetism results from an electric current. This chapter introduces readers to the unit conversion ready for the discussion in Chapter 2, which deals with the origin of magnetism in materials and introduces the concepts of electron spin, magnetic moments and its dynamics. It covers the microscopic view of the magnetic moment of an electron and an atom, and investigates its relationship with the macroscopic properties of magnetic thin film materials. Once the

film is patterned to make devices, it behaves very differently from a full film. Chapter 3 covers the properties of the patterned thin magnetic films. This leads to the discussion of magnetization switching properties of many modern magnetic RAM devices. Chapter 4 introduces the magnetoresistance effect in thin film stacks, covering AMR (anisotropy magneto-resistance), GMR (giant magneto-resistance) and TMR (tunnel magneto-resistance) effects. The magneto-resistance effect is the operational principle of all modern non-volatile magnetic memories. A thorough discussion of the magnetic tunnel junction is presented. A detailed description of the properties and the design of field-write modes magnetic memory device are given in Chapter 5 and that of spin-torque transfer mode in Chapter 6. The discussion also covers circuit aspects of the memory cell and memory array, and the circuit model of the magnetic tunnel junction device, so that one can gain a better perspective of the merits in the design of the magnetic tunnel junction for memory. Chapter 7 covers the present memory market and the position of the magnetic memory in this market. New applications of this technology will also be discussed.

This is a very active field. Papers and patent applications of the related subject appear continuously and in large quantities. This book aims to provide the reader with a sufficient understanding of the fundamental physics of magnetics, the properties of magnetic thin film materials, device properties, design, memory operation and many other aspects of engineering. It also aims to give those working with semiconductors a head start so that they may bring in more fruitful results to this relatively new field.

Acknowledgments

The authors would like to acknowledge the contribution made by their colleagues at MagIC Technologies, Inc., including Mao-min Chen, Terry Thong, Wiltold Kula, Cheng Horng, Ruth Tong, David Heim, Tai Min, Robert Beach, Guenole Jan and Karl Yang. Parts of their work are described in this book.

In addition, the authors would like to thank Stuart Parkin, William Gallagher, Jonathan Sun and Daniel Worledge of IBM; Professor Ching-Ray Chang of National Taiwan University; C.T. (Jack) Yao and Pantas Sutardja for numerous interactions; Anthony Oates of TSMC and Tak Ning of the IBM Watson Research Center, who helped us begin the writing process. The authors would also like to thank their families for lending their support during the manuscript preparation, especially Grace Tang, Pi-ju Liao and Minchene Tang.

Special thanks go also to our colleague in MagIC Technologies, Inc., Dr. Pokang Wang, for his critical reading of the manuscript and suggestions.