NANOMAGNETISM AND SPINTRON CS
Fabrication, Materials, Characterization and Applications

Editors

Arzad Nasirpour
Sahand University of Technology, Iran

Alain Nagaret
University of Bé, Iléa

Vb World Scientific
CONTENTS

Preface

PART I. INTRODUCTION

1 Concepts in Nanomagnetism and Spintronics 1
   Farzad Nasirpouri and Alain Nogaret
   1.1. Nanoscale Science and Technology 1
   1.2. Nanomagnetism 2
       1.2.1. Magnetic ordering an the nanoscale 3
       1.2.2. Magnetization reversal 5
       1.2.3. Dimensionality in magnetism 7
           1.2.3.1. Thin magnetic films 7
           1.2.3.2. Nanowires or one dimensional magnets 8
           1.2.3.3. Nanodots and superparamagnetism 11
   1.3. Spintronics 12
   References 14

PART II. FABRICATION AND GROWTH

2 Artificial Magnetic Domain Structures Realised by Focussed Ion Beam Irradiation 19
   Simon Bending, Simon Crampin and Atif Aziz
   2.1. Introduction 19
       2.1.1. Controlling magnetic anisotropy by irradiation 21
       2.1.2. Intrinsic domain wall resistivity 22
   2.2. Fabrication of Artificial Domain Structures 24
2.3. Magnetic Properties of Artificial Domain Structures 26
2.4. Angle-Dependent Domain Wall Resistivity Measurements 33
2.5. Conclusions and Outlook 41
References 43

3 Fabrication of Magnetic Nanostructures by Electron Beam Induced Deposition 45
Masaki Takeguchi and Masayuki Shimojo
3.1. Introduction 45
3.2. EBID Fabrication 47
3.3. Fabrication of Iron-Containing Nanostructures 48
3.4. Post-Deposition Heat Treatment: Fabrication of Alpha Iron Nanostructures 54
3.5. EBID with Fe(CO)$_5$ and Water Vapor: Fabrication of Magnetite Nanostructures 57
3.6. Summary 59
References 59

4 Preparation of Magnetic Nanoparticles Using Chemical Route and Functionalization for Medical Applications 63
Yuko Ichiyanagi
4.1. Introduction 63
4.2. Synthesis and Characterization of Magnetic Nanoparticles 65
4.3. Magnetic Properties of 3d Metal Hydroxide and Metal Oxide Nanoparticles 66
4.3.1. Magnetic properties of metal hydroxide nanoparticles 66
4.3.2. Metal oxide nanoparticles 71
4.4. Pluralistic Ferrite Nanoparticles 73
4.4.1. Ni-Zn ferrite nanoparticles 73
4.4.2. Mg ferrite nanoparticles 78
4.5. Functionalization of Magnetic Nanoparticles 80
4.5.1. Amino-silane coupling 80
4.5.2. Development for cell selective magnetic nanoparticles 81

4.6. Conclusions and Outlook 84

References 85

5 Electrodeposition as a Fabrication Method of Magnetic Nanostructures 89

Ldszl6 Peter and Imre Bakonyi

5.1. Introduction 89

5.2. Electrodeposition: A General Overview 90

5.2.1. Definitions and major principles 90

5.2.2. Electrodeposition of magnetic elements 94

5.2.3. Electrodeposition of magnetic alloys 94

5.2.4. Non-metallic deposits obtained with electrochemistry 96

5.3. Electrodeposition: A Route Toward Magnetic Nanostructures 96

5.3.1. Electrodeposition of ultrathin magnetic films 96

5.3.2. Nanocrystalline magnetic deposits 99

5.3.3. Deposition of metastable precursor alloys and their treatment for obtaining granular magnetic alloys 101

5.3.4. Electrodeposition of magnetic/non-magnetic multilayer films with nanometer-scale periodicity 102

5.3.5. Deposition of nanostructures at preferred nucleation sites 105

5.3.6. Electrodeposition into templates 107

5.3.7. Electrodeposition an surfaces modified by self-assembly of colloids 110

5.3.8. Suspension plating with magnetic particles 112

5.3.9. Formation of suspended magnetic particles by electrochemistry 113

5.4 Summary 113

References 115
PART III. MATERIALS AND CHARACTERISATION

6 Magnetolectric Materials for Spintronics 121
   Faik Mikailzade
   6.1. GMR and Spintronics 121
   6.2. History and Invention of Magnetoelectricity 123
   6.3. Linear Magnetolectric Effect 124
   6.4. Multiferroics 126
   6.5. Magnetolectric Composites 129
   6.6. Conclusions and Outlook 132
   References 133

7 GMR in Electrodeposited Superlattices 139
   Gholamreza Nabiyouni
   7.1. Introduction 139
   7.2. Electrodeposition 142
   7.3. Electrodeposition of Metals and Alloys 144
   7.4. Electrodeposition of Multilayers and Superlattices 146
      7.4.1. Dual bath electrodeposition 147
      7.4.2. Single bath electrodeposition 148
      7.4.3. Electrodeposition of metallic thin films onto semiconductor substrates 151
   7.5. Resistivity in Metals 153
   7.6. Magnetoresistance 153
      7.6.1. Ordinary magnetoresistance 154
      7.6.2. Anisotropic magnetoresistance 154
   7.7. Giant Magnetoresistance (GMR) 155
   7.8. Oscillatory GMR in Superlattices 158
   7.9. Research on GMR 161
   7.10. Superparamagnetism Contribution to GMR in the Electrodeposited Superlattices 164
   7.11. General Remarks on Electrodeposited Superlattices 166
   References 167
Contents

8 Introduction to Spin Transfer Torque 173
  C. Baraduc, M. Chshiev and U. Ebels
  8.1. Introduction 173
  8.2. Spin Transfer Torque 174
  8.3. A Microscopic Picture 176
  8.4. Transverse Spin Transfer Torque 179
  8.5. Magnetization Dynamics 183
    8.5.1. Conservative dynamics 184
    8.5.2. Damped dynamics 185
    8.5.3. Spin transfer torque induced dynamics 186
      8.5.3.1. Static states 186
      8.5.3.2. Stability 187
      8.5.3.3. Dynamic states 187
  8.6. State Diagram 188
    8.6.1. Planar polarizer 189
    8.6.2. Perpendicular polarizer 190
  8.7. Conclusions 190
References 191

9 Spintronics Potential of Rare-Earth Nitrides 193
  Ben J. Ruck
  9.1. Introduction 193
  9.2. Rare-Earth Nitride Preparation 195
  9.3. Electronic Structure 199
    9.3.1. Band structure calculations 199
    9.3.2. Experiment 205
  9.4. Magnetic Properties 211
  9.5. Device Prospects and Future Challenges 214
  9.6. Conclusions 218
References 218

10 Dilute Magnetic Oxides: Current Status and Prospects 223
  Karen Yates
  10.1. Introduction 223
  10.2. Impurities 225
10.2.1. Types of impurity in DMS systems 225
  10.2.1.1. Extrinsic impurities 225
  10.2.1.2. Clusters 226
  10.2.1.3. Solubility 229
  10.2.1.4. Spinels as secondary phases 231
  10.2.1.5. Other secondary phases 233

10.3. Intrinsic Mechanisms for Magnetic Behaviour 235
  10.3.1. Insulating regime 236
    10.3.1.1. Theoretical treatments 237
    10.3.1.2. Experimental results 238
    10.3.1.3. "d°" ferromagnetism 240
  10.3.2. Magnetism at high carrier concentrations 242
    10.3.2.1. Theoretical review 243
    10.3.2.2. Experimental results 244

10.4. Devices Already Made with DMS DMO and DMD Materials 250

10.5. Outlook 253

References 254

11 Mössbauer Spectroscopy and Its Applications in Spintronics 267
  Saeed Kamali

  11.1. Introduction 267
  11.2. Mössbauer Spectroscopy: The Basics 268
    11.2.1. Electric monopole interaction 270
      11.2.1.1. Isomer shift 270
      11.2.1.2. Second order Doppler shift 271
      11.2.1.3. Centroid shift 271
    11.2.2. Electrical quadrupole interaction 272
    11.2.3. Magnetic hyperfine interaction 273
    11.2.4. Combined electric and magnetic hyperfine interaction 275
    11.2.5. Transmission vs. conversion electron Mössbauer spectroscopy 275
    11.2.6. Relative intensities of resonance lines 276
11.3. Superlattices, Thin Films 277
   11.3.1. Fe/Co superlattices 278
      11.3.1.1. Magnetic hyperfine field 278
      11.3.1.2. Magnetic anisotropy energy 280
   11.3.2. Fe/Cr 280
   11.3.3. Fe/V superlattices 284
   11.3.4. Exchange spring magnets 287

References 292

12 Nuclear Resonance Scattering and Its Applications in Spintronics 297
   Saeed Kumuli
   12.1. Introduction 297
   12.2. Synchrotron Radiation 297
   12.3. Nuclear Resonance Scattering 299
   12.4. Exchange Spring Magnets 303
   12.5. Magnetic Tunnel Junctions 306
   12.6. Conclusions 311

References 311

PART IV. APPLICATIONS

13 Bionanomagnetism 315
   Peter Svedlindh, Klas Gunnarsson, Mattias Strömberg and Sven Oscarsson
   13.1. Introduction 316
   13.2. Properties and Biofunctionalisation of Magnetic Beads 318
      13.2.1. Magnetic beads 318
      13.2.2. Biofunctionalisation of magnetic beads – the SPDP coupling chemistry 319
   13.3. An Example of a Recently Developed Magnetic Biosensor Scheme — The Volume-Amplified Magnetic Nanobead Detection Assay 321
      13.3.1. Dynamic magnetic properties and relaxation mechanisms of magnetic beads 321
13.3.2. Brief overview of the volume-amplified nanobead detection assay 322
13.4. Transportation and Release of Biomolecules Using Magnetic Beads 327
13.5. Conclusions and Outlook 334
13.6. Abbreviations and Acronyms of Chapter 13 336
References 338

14 Domain Walls for Logic and Data Storage Applications 343

Colm C. Faulkner

14.1. Introduction 343
14.2. Theory 344
14.3. Wire Switching 345
14.4. Domain Wall Propagation 347
14.5. Domain Wall Injection 348
14.6. Rounded Corner Structures 351
14.7. Domain Wall Localisation/Trapping/Point Contacts 352
14.8. Domain Wall Protrusion 354
14.9. Domain Wall Chirality 355
14.10. Domain Wall Dynamics 356
14.11. DW Velocity Enhancements 358
14.11.1. Transverse field 358
14.11.2. Roughness 358
14.11.3. Current assisted 359
14.11.4. Ion irradiation 359
14.11.5. Out of plane field 359
14.12. Spin Torque 359
14.13. Domain Wall Mediated Data Storage 361
14.14. DW Racetrack Memory 361
14.15. Domain Wall Logic 362
14.16. NOT 363
14.17. AND/OR 365
14.18. Fanout/Cloning 365
14.19. Crossover 366
14.20. Data Input 368