

## Contents

### Preface *xiii*

<b>1</b>	<b>Introduction to Magnetic Materials</b>	<b>1</b>
1.1	Theory and Fundamentals of Magnetization	1
1.2	Type of Magnetism	2
1.2.1	Diamagnetism	3
1.2.2	Paramagnetism	3
1.2.3	Ferromagnetism	4
1.2.4	Antiferromagnetism	4
1.2.5	Ferrimagnetism	4
1.3	Extrinsic and Intrinsic Characteristics of Magnetic Materials	5
1.3.1	Intrinsic Properties	8
1.3.1.1	Saturation Magnetization ( $M_s$ )	8
1.3.1.2	Curie Temperature ( $T_C$ )	10
1.3.1.3	Magnetic Anisotropy	10
1.3.2	Extrinsic Properties	13
	References	14
<b>2</b>	<b>Type and Characteristics of Magnetic Materials</b>	<b>17</b>
2.1	Introduction	17
2.2	Soft and Hard Magnetic Materials	17
2.2.1	Soft Magnetic Materials	17
2.2.2	Hard Magnetic Materials	19
2.3	Hysteresis Loop	19
2.3.1	The Process of Hysteresis Loop Formation	19
2.3.2	Domain Orientation in Directions Favorable to the Applied Field	20
2.4	Magnetic Characteristic Measurements	21
2.4.1	$M-H$ Hysteresis Loop	21
2.4.2	$B-H$ Hysteresis Loop	22
2.5	Magnetic Losses	22
2.5.1	Eddy Current Losses	23
2.5.2	Residual Losses	25
2.5.3	Hysteresis Losses	25
	References	26

<b>3</b>	<b>Insight into the Synthesis of Nanostructured Magnetic Materials</b>	<b>29</b>
3.1	Introduction	29
3.2	Synthesis Process of the Magnetic Nanoparticles	30
3.3	Importance of the Synthesis and/or Preparation Methods	31
3.4	Dependency of Particle Size and Shape on Synthesize Route	32
3.5	Questions Related to the Selected Synthesis Route	33
3.6	Dependency of Magnetic Behaviors on Particle/Grain Size	38
3.7	Dependency of Magnetic Behaviors on Particle/Grain Shape	40
3.8	Introduction to Wet-Chemical Synthesis Route	41
3.8.1	Microemulsion	43
3.8.2	Hydrothermal Method	43
3.8.3	Co-precipitation	44
3.8.4	Sonochemical	44
3.8.5	Sol-Gel Method	44
3.8.6	Thermal Decomposition	45
3.8.7	Solvothermal	45
3.8.8	Microwave-Assisted Route	45
3.8.9	Green-Assisted Synthesis Route	45
3.9	Introduction to Solid-State Routes to Synthesize Magnetic Nanoparticles	46
3.9.1	A Standard Ceramic Route	46
3.9.2	Mechanical Alloying (MA) Process	46
3.10	Some Methods for Extraction of Iron Oxide Nanoparticles from Industrial Wastes	50
3.10.1	Magnetic Separation Technique (MST)	50
3.10.2	Curie Temperature Separation Technique	50
3.10.3	Oxidation of Wuestite	50
	References	51
<b>4</b>	<b>Parallel Evolution of Microstructure-Magnetic Properties Relationship in Nanostructured Ferrites</b>	<b>59</b>
4.1	Introduction	59
4.2	Insights into a Sintering Phenomenon	62
4.2.1	Magnetism-Microstructure Parallel Evolution in Yttrium Iron Garnet	68
4.2.2	Magnetism-Microstructure Parallel Evolution in Hard Ferrites	71
4.2.3	Magnetism-Microstructure Parallel Evolution in Soft Ferrites	80
4.3	Soaking or Sintering Time	84
4.4	Heating Rate	88
4.5	Trends of Sintering: Single-Sample and Multi-Sample Sintering	89
4.6	Conclusion and Perspective Outlook	91
	References	92

<b>5</b>	<b>Surface Modification of Magnetic Nanoparticles</b>	<b>99</b>
5.1	Introduction	99
5.2	Employed Technical Resources for Surface Modification	99
5.2.1	Plasma Treatment	99
5.2.2	Corona Discharge	100
5.2.3	Parylene Coating	101
5.2.4	Photolysis	101
5.2.5	Other Methods and Examples	101
5.3	Surface Modification of Magnetic Nanoparticles with Surfactant	103
5.4	Current Trends for Surface Modification of Nanomaterials	105
5.4.1	Chemical Functionalization	105
5.4.2	Physical Functionalization	106
5.5	Surface Modification Based on Organic Reactions	108
5.6	Surface Modification Based on Polymerization	109
5.7	Surface Modification with Inorganic Layers	110
5.8	Summary	111
	References	112
<b>6</b>	<b>Insight into Superconducting Quantum Interference Devices (SQUID)</b>	<b>117</b>
6.1	Introduction to SQUID	117
6.1.1	A Radio Frequency (RF) SQUID	117
6.1.2	A Direct Current (DC) SQUID	119
6.2	Superconducting Materials Used in SQUID	120
6.3	What Is the Basic Principle in SQUID VSM Magnetometer?	121
6.4	Superconductivity	121
6.4.1	Electron–Lattice Interaction	123
6.4.2	Cooper Pairs	124
6.4.3	Energy Gap	124
6.4.4	Coherence	125
6.4.5	Flux Quantization	125
6.5	Josephson Tunneling (JT) Phenomenon	125
6.6	Utilizations and Applications of SQUID	127
6.7	Advantage and Disadvantage of SQUID Compared to Other Techniques in Characterization of Magnetic Nanomaterials	128
	References	131
<b>7</b>	<b>The Principle of SQUID Magnetometry and Its Contribution in MNPs Evaluation</b>	<b>135</b>
7.1	Introduction	135
7.2	The Correct Procedure to Perform the Zero Field Cooling (ZFC) and Field Cooling (FC) Magnetic Study	136
7.3	The Concept of Merging Zero Field Cooled (ZFC) and Field Cooled (FC) Curve Completely with Each Other	137

7.4	Types of Information Obtained from the ZFC and FC Curves	138
7.4.1	Blocking Temperature	138
7.4.2	Néel Temperature	140
7.4.3	Types of Magnetism	140
7.4.4	Spin Glass (SG) and Superparamagnetic (SPM)	140
7.5	SQUID Magnetometry: Magnetic Measurements	141
7.5.1	Magnetization Versus Temperature, $M(T)$	141
7.5.1.1	Blocking Temperature ( $T_B$ ) as a Function of Particle Size Distribution	141
7.5.1.2	Dependency of Blocking Temperature ( $T_B$ ) on the Volume of Particles	144
7.5.1.3	The Field Dependence of the Blocking Temperature	144
7.5.1.4	The Blocking Temperature ( $T_B$ ) Versus Applied Pressure, and Density	146
7.5.1.5	Effect of Heat Treatment on Blocking Temperature	147
7.5.2	Magnetization as a Function of Applied Magnetic Field	148
	References	149
<b>8</b>	<b>Type of Interactions in Magnetic Nanoparticles</b>	<b>157</b>
8.1	Introduction	157
8.2	Magnetic Dipole–Dipole Interaction Between Magnetic Nanoparticles	157
8.3	Exchange Interaction	158
8.3.1	Direct Exchange Interaction	159
8.3.2	Indirect Exchange Interaction	160
8.4	Super-Exchange Interaction	163
8.5	Dipolar Interactions	165
8.6	Spin–Orbit Interaction	165
	References	166
<b>9</b>	<b>Insight into AC Susceptibility Measurements in Nanostructured Magnetic Materials</b>	<b>169</b>
9.1	Introduction	169
9.2	AC Susceptibility Measurement	170
9.3	AC Susceptibility as a Probe of Magnetic Dynamics in a Wide Variety of Systems	172
9.3.1	AC Susceptibility as a Probe of Low-Frequency Magnetic Dynamics	172
9.3.2	AC Susceptibility as a Probe of High-Frequency Magnetic Dynamics	172
9.4	Information Obtained from Susceptibility Measurements	173
9.5	Insight into the Interaction Between Magnetic Nanoparticles and Used Models	174
9.5.1	Néel–Brown Model	174
9.5.2	Vogel–Fulcher Model	175

9.5.3	Conventional Critical Slowing Down Model	176
9.5.4	Power Law (P-L) Model	176
9.6	Examples of Evaluation of AC Susceptibility in MNPs	177
9.7	Using AC Susceptibility Measurements to Probe Transitions in Colloidal Suspensions	188
	References	191
<b>10</b>	<b>Induced Effects in Nanostructured Magnetic Materials</b>	<b>197</b>
10.1	Introduction	197
10.2	The Spin-Canted Effect	197
10.3	Spin-Glass-Like Behavior in Magnetic Nanoparticles	200
10.4	Reentrant Spin Glass (RSG) Behavior in Magnetic Nanoparticles	203
10.5	Finite Size Effects on Magnetic Properties	206
10.6	Surface Effect in Nanosized Particles	207
10.7	Memory Effect	208
	References	210
<b>11</b>	<b>Insight into Superparamagnetism in Magnetic Nanoparticles</b>	<b>219</b>
11.1	Introduction	219
11.2	Description of Superparamagnetism Based on Size of Particles and Magnetic Measurements	219
11.3	SPM Description Based on Magnetization Hysteresis Loop ( $M-H$ or $B-H$ )	228
11.4	SPM Detection Based on ZFC and FC Magnetization Curves	229
	References	230
<b>12</b>	<b>Mössbauer Spectroscopy</b>	<b>233</b>
12.1	Introduction to Mössbauer Spectroscopy	233
12.2	Observed Effects in Mössbauer	235
12.2.1	Mössbauer Effect	235
12.2.2	Recoil Effect	235
12.2.3	Doppler Effect	237
12.3	Hyperfine Interactions	238
12.3.1	Electric Monopole Interaction	238
12.3.1.1	S-Electron Density (Indirectly p and d-Electron Density)	240
12.3.1.2	Dependency of Isomer Shift on Spin State	241
12.3.1.3	Dependency of Isomer Shift on Strong Field Ligands	241
12.3.1.4	Dependency of Isomer Shift on Electronegativity of Ligands	241
12.3.2	Electric Quadrupole Interaction (Quadrupole Splitting)	242
12.3.3	Magnetic Dipole Interaction (Magnetic Splitting)	244
12.4	Mössbauer Spectroscopy Applied to Magnetism	246
12.4.1	Superparamagnetic Characterization	247

12.4.2	Mössbauer Spectroscopy Applied to Characterize the Effect of Synthesis Method on the MNPs Behavior	254
12.5	Phase Formation Evaluation Through Mössbauer Spectroscopy	274
12.6	Chemical Composition Evaluation Based on the Mössbauer Spectroscopy Spectra	281
	References	284
<b>13</b>	<b>Application of Magnetic Nanoparticles</b>	<b>295</b>
13.1	Introduction	295
13.2	Magnetic Nanoparticles: Application in Engineering	295
13.2.1	Mechanical and Materials Engineering: Magnetic Nanoparticles in Magnetorheological Fluids (MRF)	295
13.2.2	Environmental Engineering: Magnetic Nanoparticles in Wastewater Treatment	296
13.2.3	Surface Engineering	300
13.2.4	Tissue Engineering (TE)	300
13.3	Magnetic Nanoparticle Application in Energy	301
13.3.1	Supercapacitors and Batteries	301
13.3.2	Solar Cells	301
13.4	Magnetic Nanoparticles Application in Medical Science	302
13.4.1	Magnetic Resonance Imaging (MRI)	303
13.4.2	Drug Delivery	304
13.4.3	An Introduction to Hyperthermia (Therapy) in Cancer Treatment (Methods, Mechanisms, Constraints, and Role of Nanotechnology)	306
13.4.3.1	Magnetic Loss Processes Contributed to Magnetic Heating	307
13.4.3.2	Challenges of Magnetic Hyperthermia for Therapeutic Uses	309
13.5	Other General Applications of Magnetic Nanoparticles	313
	References	313
	<b>Index</b>	<b>321</b>