Contents

Acknowledgments *page* xiii

I Basics

1 Review of basic magnetostatics 3

1.1 Magnetic field 4

1.1.1 Magnetic poles 4

1.1.2 Magnetic flux 6

1.1.3 Circulating currents 6

1.1.4 Ampère's circuital law 7

1.1.5 Biot–Savart law 8

1.1.6 Field from a straight wire 8

1.2 Magnetic moment 10

1.2.1 Magnetic dipole 11

1.3 Definitions 11

Homework 12

2 Magnetization and magnetic materials 14

2.1 Magnetic induction and magnetization 14

2.2 Flux density 15

2.3 Susceptibility and permeability 16

2.4 Hysteresis loops 18

2.5 Definitions 19

2.6 Units and conversions 19

Homework 20

3 Atomic origins of magnetism 22

3.1 Solution of the Schrödinger equation for a free atom 22

3.1.1 What do the quantum numbers represent? 25

3.2 The normal Zeeman effect 27

3.3 Electron spin 30
3.4 Extension to many-electron atoms 31
3.4.1 Pauli exclusion principle 32
3.5 Spin–orbit coupling 32
3.5.1 Russell–Saunders coupling 32
3.5.2 Hund's rules 34
3.5.3 *jj* coupling 35
3.5.4 The anomalous Zeeman effect 35
Homework 37
4 Diamagnetism 38
4.1 Observing the diamagnetic effect 38
4.2 Diamagnetic susceptibility 39
4.3 Diamagnetic substances 41
4.4 Uses of diamagnetic materials 42
4.5 Superconductivity 42
4.5.1 The Meissner effect 43
4.5.2 Critical field 44
4.5.3 Classification of superconductors 44
4.5.4 Superconducting materials 44
4.5.5 Applications for superconductors 46
Homework 46
5 Paramagnetism 48
5.1 Langevin theory of paramagnetism 49
5.2 The Curie–Weiss law 52
5.3 Quenching of orbital angular momentum 54
5.4 Pauli paramagnetism 55
5.4.1 Energy bands in solids 56
5.4.2 Free-electron theory of metals 58
5.4.3 Susceptibility of Pauli paramagnets 60
5.5 Paramagnetic oxygen 62
5.6 Uses of paramagnets 63
Homework 64
6 Interactions in ferromagnetic materials 65
6.1 Weiss molecular field theory 66
6.1.1 Spontaneous magnetization 66
6.1.2 Effect of temperature on magnetization 67
6.2 Origin of the Weiss molecular field 69
6.2.1 Quantum mechanics of the He atom 70
6.3 Collective-electron theory of ferromagnetism 73
6.3.1 The Slater–Pauling curve 76

6.4 Summary 76
Homework 78
7 Ferromagnetic domains 79
7.1 Observing domains 79
7.2 Why domains occur 81
7.2.1 Magnetostatic energy 81
7.2.2 Magnetocrystalline energy 82
7.2.3 Magnetostrictive energy 84
7.3 Domain walls 85
7.4 Magnetization and hysteresis 87
Homework 92
8 Antiferromagnetism 96
8.1 Neutron diffraction 97
8.2 Weiss theory of antiferromagnetism 101
8.2.1 Susceptibility above T_N 102
8.2.2 Weiss theory at T_N 103
8.2.3 Spontaneous magnetization below T_N 103
8.2.4 Susceptibility below T_N 103
8.3 What causes the negative molecular field? 107
8.4 Uses of antiferromagnets 110
Homework 112
9 Ferrimagnetism 113
9.1 Weiss theory of ferrimagnetism 114
9.1.1 Weiss theory above T_C 115
9.1.2 Weiss theory below T_C 117
9.2 Ferrites 120
9.2.1 The cubic ferrites 120
9.2.2 The hexagonal ferrites 124
9.3 The garnets 125
9.4 Half-metallic antiferromagnets 126
Homework 127
10 Summary of basics 130
10.1 Review of types of magnetic ordering 130
10.2 Review of physics determining types of magnetic ordering 131
II Magnetic phenomena
11 Anisotropy 135
11.1 Magnetocrystalline anisotropy 135
11.1.1 Origin of magnetocrystalline anisotropy 136
11.1.2 Symmetry of magnetocrystalline anisotropy 138

11.2 Shape anisotropy 139
11.2.1 Demagnetizing field 139
11.3 Induced magnetic anisotropy 141
11.3.1 Magnetic annealing 141
11.3.2 Roll anisotropy 142
11.3.3 Explanation for induced magnetic anisotropy 142
11.3.4 Other ways of inducing magnetic anisotropy 143
Homework 144
12 Nanoparticles and thin films 145
12.1 Magnetic properties of small particles 145
12.1.1 Experimental evidence for single-domain particles 147
12.1.2 Magnetization mechanism 147
12.1.3 Superparamagnetism 148
12.2 Thin-film magnetism 152
12.2.1 Structure 152
12.2.2 Interfaces 153
12.2.3 Anisotropy 153
12.2.4 How thin is thin? 154
12.2.5 The limit of two-dimensionality 154
13 Magnetoresistance 156
13.1 Magnetoresistance in normal metals 157
13.2 Magnetoresistance in ferromagnetic metals 158
13.2.1 Anisotropic magnetoresistance 158
13.2.2 Magnetoresistance from spontaneous magnetization 159
13.2.3 Giant magnetoresistance 160
13.3 Colossal magnetoresistance 164
13.3.1 Superexchange and double exchange 164
Homework 168
14 Exchange bias 169
14.1 Problems with the simple cartoon mechanism 171
14.1.1 Ongoing research on exchange bias 172
14.2 Exchange anisotropy in technology 173
III Device applications and novel materials
15 Magnetic data storage 177
15.1 Introduction 177
15.2 Magnetic media 181
15.2.1 Materials used in magnetic media 181
15.2.2 The other components of magnetic hard disks 183
15.3 Write heads 183

15.4 Read heads 185
15.5 Future of magnetic data storage 186
16 Magneto-optics and magneto-optic recording 189
16.1 Magneto-optics basics 189
16.1.1 Kerr effect 189
16.1.2 Faraday effect 191
16.1.3 Physical origin of magneto-optic effects 191
16.2 Magneto-optic recording 193
16.2.1 Other types of optical storage, and the future of magneto-optic recording 196
17 Magnetic semiconductors and insulators 197
17.1 Exchange interactions in magnetic semiconductors and insulators 198
17.1.1 Direct exchange and superexchange 199
17.1.2 Carrier-mediated exchange 199
17.1.3 Bound magnetic polarons 200
17.2 II–VI diluted magnetic semiconductors – (Zn,Mn)Se 201
17.2.1 Enhanced Zeeman splitting 201
17.2.2 Persistent spin coherence 202
17.2.3 Spin-polarized transport 203
17.2.4 Other architectures 204
17.3 III–V diluted magnetic semiconductors – (Ga,Mn)As 204
17.3.1 Rare-earth–group-V compounds – ErAs 207
17.4 Oxide-based diluted magnetic semiconductors 208
17.5 Ferromagnetic insulators 210
17.5.1 Crystal-field and Jahn–Teller effects 210
17.5.2 $YTiO_3$ and $SeCuO_3$ 211
17.5.3 $BiMnO_3$ 213
17.5.4 Europium oxide 214
17.5.5 Double perovskites 215
17.6 Summary 215
18 Multiferroics 216
18.1 Comparison of ferromagnetism and other types of ferroic ordering 216
18.1.1 Ferroelectrics 216
18.1.2 Ferroelastics 219
18.1.3 Ferrotoroidics 220
18.2 Multiferroics that combine magnetism and ferroelectricity 221
18.2.1 The contra-indication between magnetism and ferroelectricity 222

18.2.2 Routes to combining magnetism and ferroelectricity 223
18.2.3 The magnetoelectric effect 225
18.3 Summary 228
Epilogue 229
Solutions to selected exercises 230
References 262
Index 270