

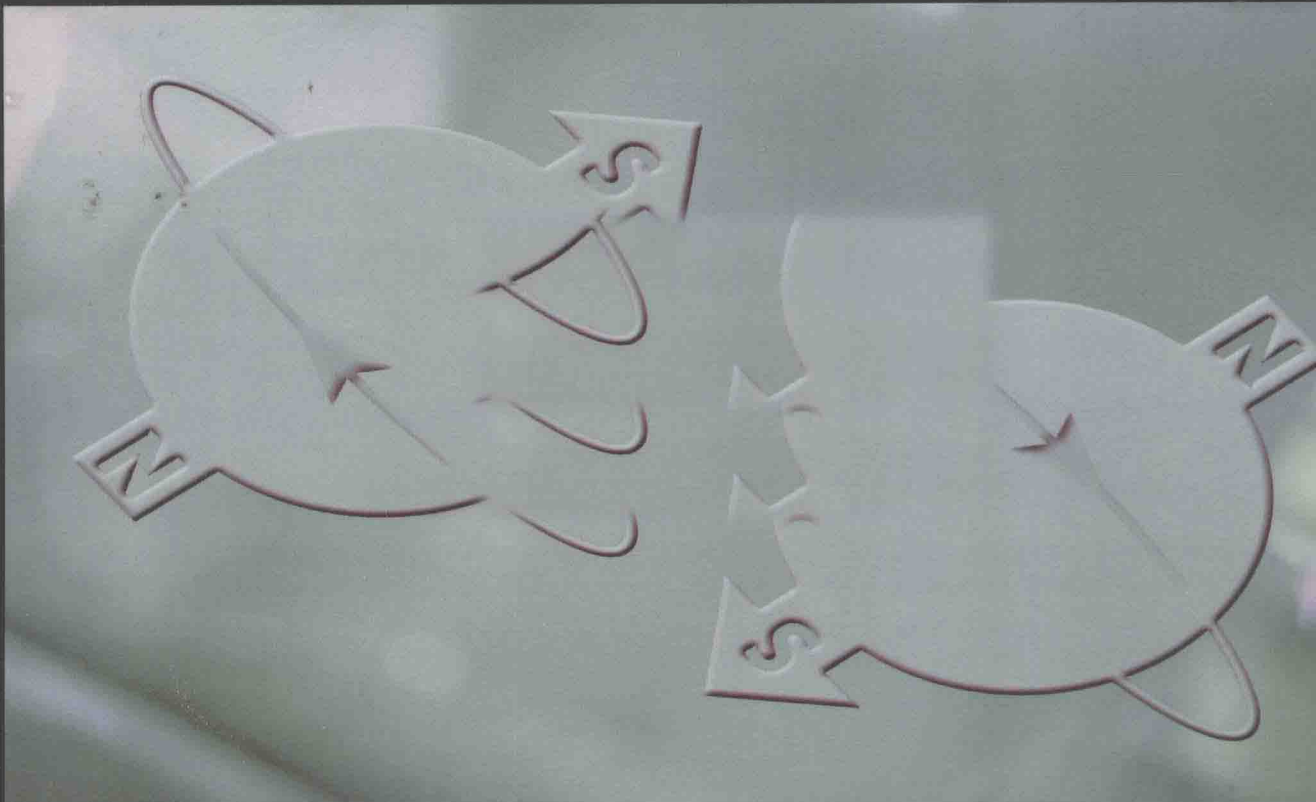
Nicola A. Spaldin

Magnetic Materials

Fundamentals and Applications

Second Edition

磁性材料 第2版



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MAGNETIC MATERIALS

Fundamentals and Applications

Second edition

NICOLA A. SPALDIN

University of California, Santa Barbara



CAMBRIDGE
UNIVERSITY PRESS

图书在版编目 (CIP) 数据

磁性材料 = Magnetic materials: 第 2 版: 英文/ (美) 斯波尔丁 (Spaldin, N. A.)
著. —影印本. —北京: 世界图书出版公司北京公司, 2014. 10
ISBN 978 - 7 - 5100 - 8771 - 4

I. ①磁… II. ①斯… III. ①磁性材料—英文 IV. ① O4

中国版本图书馆 CIP 数据核字 (2014) 第 241257 号

书 名: Magnetic Materials: Fundamentals and Applications 2nd ed.

作 者: Nicola A. Spaldin

中译名: 磁性材料 第 2 版

责任编辑: 高蓉 刘慧

出 版 者: 世界图书出版公司北京公司

印 刷 者: 三河市国英印务有限公司

发 行 者: 世界图书出版公司北京公司 (北京朝内大街 137 号 100010)

联系电话: 010 - 64021602, 010 - 64015659

电子信箱: kjb@wpchj. com. cn

开 本: 16 开

印 张: 18

版 次: 2015 年 3 月

版权登记: 图字: 01 - 2013 - 4910

书 号: 978 - 7 - 5100 - 8771 - 4

定 价: 79.00 元

MAGNETIC MATERIALS

Fundamentals and Applications

Magnetic Materials is an excellent introduction to the basics of magnetism, magnetic materials, and their applications in modern device technologies. Retaining the concise style of the original, this edition has been thoroughly revised to address significant developments in the field, including the improved understanding of basic magnetic phenomena, new classes of materials, and changes to device paradigms. With homework problems, solutions to selected problems, and a detailed list of references, *Magnetic Materials* continues to be the ideal book for a one-semester course and as a self-study guide for researchers new to the field.

New to this edition:

- Entirely new chapters on exchange-bias coupling, multiferroic and magnetoelectric materials, and magnetic insulators
- Revised throughout, with substantial updates to the chapters on magnetic recording and magnetic semiconductors, incorporating the latest advances in the field
- New example problems with worked solutions

NICOLA A. SPALDIN is a Professor in the Materials Department at the University of California, Santa Barbara. She is an enthusiastic and effective teacher, with experience ranging from developing and managing the UCSB Integrative Graduate Training Program to answering elementary school students' questions online. Particularly renowned for her research in multiferroics and magnetoelectrics, her current research focuses on using electronic structure methods to design and understand materials that combine magnetism with additional functionalities. She was recently awarded the American Physical Society's McGroddy Prize for New Materials for this work. She is also active in research administration, directing the UCSB/National Science Foundation International Center for Materials Research.

Magnetic Materials: Fundamentals and Applications Second Edition (978-0-521-88669-7) by Nicola A. Spaldin, first published by Cambridge

University Press 2011

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Magnus magnes ipse est globus terrestris.
William Gilbert, *De Magnete*. 1600.

Acknowledgments

This book has been tested on human subjects during a course on Magnetic Materials that I have taught at UC Santa Barbara for the last decade. I am immensely grateful to each class of students for suggesting improvements, hunting for errors, and letting me know when I am being boring. I hope that their enthusiasm is contagious.

Nicola Spaldin

Contents

<i>Acknowledgments</i>	<i>page</i> 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	<i>jj</i> 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
<i>Epilogue</i>	229
<i>Solutions to selected exercises</i>	230
<i>References</i>	262
<i>Index</i>	270

Part I

Basics

1

Review of basic magnetostatics

Mention magnetism and an image arises of musty physics labs peopled by old codgers with iron filings under their fingernails.

John Simonds, *Magnetoelectronics today and tomorrow*,
Physics Today, April 1995

Before we can begin our discussion of magnetic materials we need to understand some of the basic concepts of magnetism, such as what causes magnetic fields, and what effects magnetic fields have on their surroundings. These fundamental issues are the subject of this first chapter. Unfortunately, we are going to immediately run into a complication. There are two complementary ways of developing the theory and definitions of magnetism. The “physicist’s way” is in terms of circulating currents, and the “engineer’s way” is in terms of magnetic poles (such as we find at the ends of a bar magnet). The two developments lead to different views of which interactions are more fundamental, to slightly different-looking equations, and (to really confuse things) to two different sets of units. Most books that you’ll read choose one convention or the other and stick with it. Instead, throughout this book we are going to follow what happens in “real life” (or at least at scientific conferences on magnetism) and use whichever convention is most appropriate to the particular problem. We’ll see that it makes most sense to use *Système International d’Unités* (SI) units when we talk in terms of circulating currents, and centimeter–gram–second (cgs) units for describing interactions between magnetic poles.

To avoid total confusion later, we will give our definitions in this chapter and the next from *both* viewpoints, and provide a conversion chart for units and equations at the end of Chapter 2. Reference [1] provides an excellent light-hearted discussion of the unit systems used in describing magnetism.

1.1 Magnetic field

1.1.1 Magnetic poles

So let's begin by defining the magnetic field, H , in terms of magnetic poles. This is the order in which things happened historically – the law of interaction between magnetic poles was discovered by Michell in England in 1750, and by Coulomb in France in 1785, a few decades before magnetism was linked to the flow of electric current. These gentlemen found empirically that the force between two magnetic poles is proportional to the product of their pole strengths, p , and inversely proportional to the square of the distance between them,

$$F \propto \frac{p_1 p_2}{r^2}. \quad (1.1)$$

This is analogous to Coulomb's law for electric charges, with one important difference – scientists believe that single magnetic poles (magnetic monopoles) do not exist. They can, however, be approximated by one end of a very long bar magnet, which is how the experiments were carried out. By convention, the end of a freely suspended bar magnet which points towards magnetic north is called the north pole, and the opposite end is called the south pole.¹ In cgs units, the constant of proportionality is unity, so

$$F = \frac{p_1 p_2}{r^2} \quad (\text{cgs}), \quad (1.2)$$

where r is in centimeters and F is in dynes. Turning Eq. (1.2) around gives us the definition of pole strength:

A pole of unit strength is one which exerts a force of 1 dyne on another unit pole located at a distance of 1 centimeter.

The unit of pole strength does not have a name in the cgs system.

In SI units, the constant of proportionality in Eq. (1.1) is $\mu_0/4\pi$, so

$$F = \frac{\mu_0}{4\pi} \frac{p_1 p_2}{r^2} \quad (\text{SI}), \quad (1.3)$$

where μ_0 is called the permeability of free space, and has the value $4\pi \times 10^{-7}$ weber/(ampere meter) (Wb/(A m)). In SI, the pole strength is measured in ampere meters (A m), the unit of force is of course the newton (N), and 1 newton = 10^5 dyne (dyn).

¹ Note, however, that if we think of the earth's magnetic field as originating from a bar magnet, then the *south* pole of the earth's "bar magnet" is actually at the magnetic north pole!