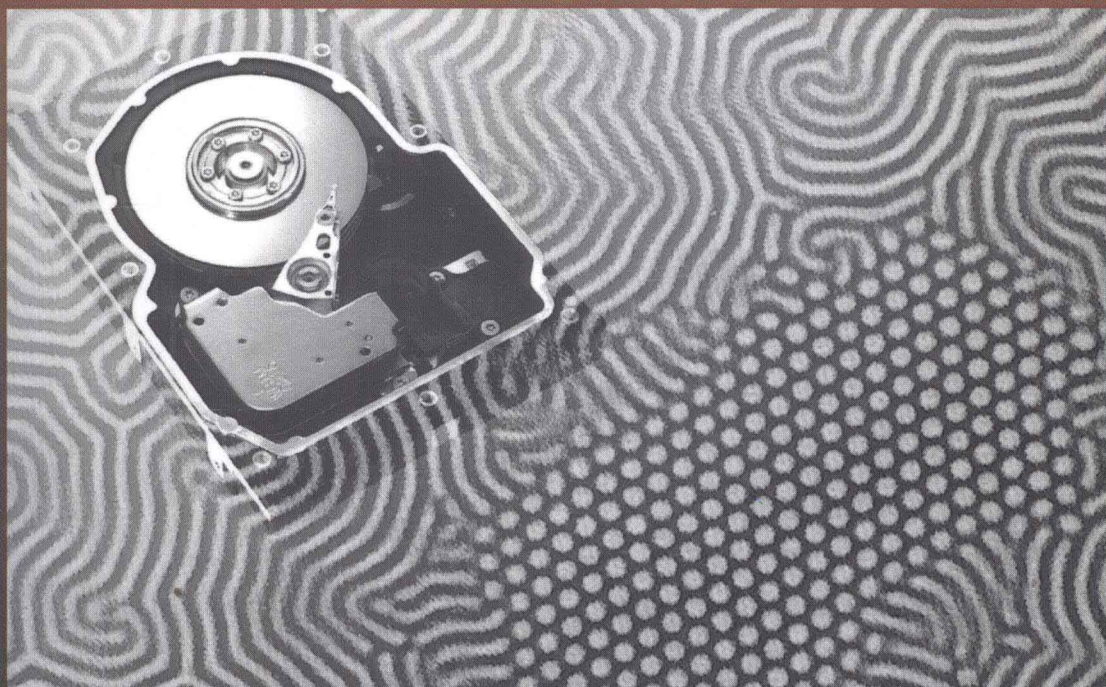




SELECTED BY GRENOBLE SCIENCES

# **Magnetism**

## **Materials & Applications**



*edited by*

***É. du Trémolet de  
Lacheisserie***

***D. Gignoux - M. Schlenker***

# **MAGNETISM**

## *Materials and Applications*

Edited by

**Étienne du TRÉMOLET de LACHEISSERIE  
Damien GIGNOUX  
Michel SCHLENKER**

**Springer**

eBook ISBN: 0-387-23063-7  
Print ISBN: 0-387-23000-9

©2005 Springer Science + Business Media, Inc.

Print ©2005 Springer Science + Business Media, Inc.  
Boston

All rights reserved

No part of this eBook may be reproduced or transmitted in any form or by any means, electronic, mechanical, recording, or otherwise, without written consent from the Publisher

Created in the United States of America

Visit Springer's eBookstore at:  
and the Springer Global Website Online at:

<http://ebooks.kluweronline.com>  
<http://www.springeronline.com>

# **MAGNETISM**

*Materials and Applications*

Front Cover Photo:

Courtesy of Pierre Molho, Laboratoire Louis Néel du CNRS, Grenoble, France. A computer hard disk drive, a device combining many state-of-the-art magnetic technologies (courtesy of Seagate Corporation). The unit is set against a magnetic domain pattern in a garnet film, imaged through the magneto-optical Faraday effect; the domain width is about 7  $\mu\text{m}$  (courtesy Pierre Molho, Laboratoire Louis Néel du CNRS, Grenoble, France).

# *AUTHORS*

**Michel CYROT** - Professor at the Joseph Fourier University of Grenoble, France

**Michel DÉCORPS** - Senior Researcher, INSERM (French Institute of Health and Medical Research), Bioclinical Magnetic Nuclear Resonance Unit, Grenoble

**Bernard DIÉNY** - Researcher and group leader at the CEA (French Atomic Energy Center), Grenoble

**Etienne du TRÉMOLET de LACHEISSERIE** - Senior Researcher, CNRS, Laboratoire Louis Néel, Grenoble

**Olivier GEOFFROY** - Assistant Professor at the Joseph Fourier University of Grenoble

**Damien GIGNOUX** - Professor at the Joseph Fourier University of Grenoble

**Ian HEDLEY** - Researcher at the University of Geneva, Switzerland

**Claudine LACROIX** - Senior Researcher, CNRS, Laboratoire Louis Néel, Grenoble

**Jean LAFOREST** - Research Engineer, CNRS, Laboratoire Louis Néel, Grenoble

**Philippe LETHUILLIER** - Engineer at the Joseph Fourier University of Grenoble

**Pierre MOLHO** - Researcher, CNRS, Laboratoire Louis Néel, Grenoble

**Jean-Claude PEUZIN** - Senior Researcher, CNRS, Laboratoire Louis Néel, Grenoble

**Jacques PIERRE** - Senior Researcher, CNRS, Laboratoire Louis Néel, Grenoble

**Jean-Louis PORTESEIL** - Professor at the Joseph Fourier University of Grenoble

**Pierre ROCHETTE** - Professor at the University of Aix-Marseille 3, France

**Michel-François ROSSIGNOL** - Professor at the Institut National Polytechnique de Grenoble (Technical University)

**Yves SAMSON** - Researcher and group leader at the CEA (French Atomic Energy Center) in Grenoble

**Michel SCHLENKER** - Professor at the Institut National Polytechnique de Grenoble (Technical University)

**Christoph SEGEBARTH** - Senior Researcher, INSERM (French Institute of Health and Medical Research), Bioclinical Magnetic Nuclear Resonance Unit, Grenoble

**Yves SOUCHE** - Research Engineer, CNRS, Laboratoire Louis Néel, Grenoble

**Jean-Paul YONNET** - Senior Researcher, CNRS, Electrical Engineering Laboratory, Institut National Polytechnique de Grenoble (Technical University)

## *Grenoble Sciences*

“Grenoble Sciences” was created ten years ago by the Joseph Fourier University of Grenoble, France (Science, Technology and Medicine) to select and publish original projects. Anonymous referees choose the best projects and then a Reading Committee interacts with the authors as long as necessary to improve the quality of the manuscript.

(Contact : Tél.: (33)4 76 51 46 95 - E-mail : Grenoble.Sciences@ujf-grenoble.fr)

The “Magnetism” Reading Committee included the following members :

- ◆ **V. Archambault**, Engineer - Rhodia-Recherche, Aubervilliers, France
- ◆ **E. Burzo**, Professor at the University of Cluj, Rumania
- ◆ **I. Campbell**, Senoir Researcher - CNRS, Orsay, France
- ◆ **F. Claeyssen**, Engineer - CEDRAT, Grenoble, France
- ◆ **G. Couderchon**, Engineer - Imphy Ugine Précision, Imphy, France
- ◆ **J.M.D. Coey**, Professor - Trinity College, Dublin, Ireland
- ◆ **A. Fert**, Professor - INSA, Toulouse, France
- ◆ **D. Givord**, Senior Researcher - Laboratoire Louis Néel, Grenoble, France
- ◆ **L. Néel**, Professor, Nobel Laureate in Physics, Member of the French Academy of Science
- ◆ **B. Raquet**, Assistant Professor - INSA, Toulouse, France
- ◆ **A. Rudi**, Engineer - ECIA, Audincourt, France
- ◆ **Ph. Tenaud**, Engineer - UGIMAG, St-Pierre d’Allevard, France

“Magnetism” (2 volumes) is an improved version of the French book published by “Grenoble Sciences” in partnership with EDP Sciences with support from the French Ministry of Higher Education and Research and the “Région Rhône-Alpes”.

# BRIEF CONTENTS

## I - FUNDAMENTALS

### Foreword

#### Phenomenological approach to magnetism

- 1 Magnetism, from the dawn of civilization to today - *E. du Trémolet de Lacheisserie*
- 2 Magnetostatics - *D. Gignoux, J.C. Peuzin*
- 3 Phenomenology of magnetism at the macroscopic scale - *D. Gignoux*
- 4 Phenomenology of magnetism at the microscopic scale - *D. Gignoux*
- 5 Ferromagnetism of an ideal system - *M. Rossignol, M. Schlenker, Y. Samson*
- 6 Irreversibility of magnetization processes, and hysteresis in real ferromagnetic materials: the role of defects - *M. Rossignol*

#### Theoretical approach to magnetism

- 7 Magnetism in the localised electron model - *D. Gignoux*
- 8 Magnetism in the itinerant electron model - *M. Cyrot*
- 9 Exchange interactions - *C. Lacroix, M. Cyrot*
- 10 Thermodynamic aspects of magnetism - *M. Schlenker, E. du T. de Lacheisserie*

#### Coupling phenomena

- 11 Magnetocaloric coupling and related effects - *E. du Trémolet de Lacheisserie, M. Schlenker*
- 12 Magnetoelastic effects - *E. du Trémolet de Lacheisserie*
- 13 Magneto-optical effects - *M. Schlenker, Y. Souche*
- 14 Magnetic resistivity, magnetoresistance, and the Hall effect - *J. Pierre*

#### Appendices

- 1 Symbols used in the text
- 2 Units and universal constants
- 3 Periodic table of the elements
- 4 Magnetic susceptibilities
- 5 Ferromagnetic materials
- 6 Special functions
- 7 Maxwell's equations

#### General references

#### Index by material and by subject



## ***II - MATERIALS AND APPLICATIONS***

### **Foreword**

#### **Magnetic materials and their applications**

- 15 Permanent magnets - *M. Rossignol, J.P. Yonnet*
- 16 Soft materials for electrical engineering and low frequency electronics - *O. Geoffroy, J.L. Porteseil*
- 17 Soft materials for high frequency electronics - *J.C. Peuzin*
- 18 Magnetostrictive materials - *E. du Trémolet de Lacheisserie*
- 19 Superconductivity - *M. Cyrot*
- 20 Magnetic thin films and multilayers - *B. Dieny*
- 21 Principles of magnetic recording - *J.C. Peuzin*
- 22 Ferrofluids - *P. Molho*

#### **Other aspects of magnetism**

- 23 Magnetic resonance imaging - *M. Décorps, C. Segebarth*
- 24 Magnetism of earth materials and geomagnetism - *P. Rochette, I. Hedley*
- 25 Magnetism and the Life Sciences - *E. du Trémolet de Lacheisserie, P. Rochette*
- 26 Practical magnetism and instrumentation - *Ph. Lethuillier*

#### **Appendices**

- 1 Symbols used in the text
- 2 Units and universal constants
- 3 Periodic table of the elements
- 4 Magnetic susceptibilities
- 5 Ferromagnetic materials
- 6 Economic aspects of magnetic materials - *J. Laforest*

#### **General references**

#### **Index by material and by subject**

## *FOREWORD*

Thousands of years before our time, our ancestors already knew about the amazing properties of lodestone, or magnetite. Ever since, man has been fascinated by magnetic phenomena, especially because of their action at a distance. They are found everywhere in our daily lives: in refrigerator doors, cars, cellphones, suspension systems for high speed trains etc. In pure science they are present at all scales, from elementary particles through to galaxy clusters, not forgetting their role in the structure and history of our Earth.

The last thirty years have seen considerable progress in most of these fields, whether fundamental or technological. The purpose of this book is to present this progress. It is the collective work of faculty members and researchers, most of whom work in laboratories in Grenoble (Universities, CNRS, CEA), often in close cooperation with local industry, and the large international organizations established in the Grenoble area: Institut Laue-Langevin, ESRF (large European synchrotron), etc. This is no surprise, since activities concerning Magnetism have consistently been supported in Grenoble ever since the beginning of the 20<sup>th</sup> century.

Most of the chapters are accessible to the University graduate in science. Those notions which require a little more maturity do not need to be fully mastered to be able to understand what comes next. This treatise should be read by all who intend to work in the field of magnetism, such an open-ended field, rich in potential for further development.

New magnets, with higher performance and lower cost, will surely be found. The magnetic properties of materials containing unfilled electronic shells are not yet fully understood. Hysteresis plays a key role in irreversible effects. While its behavior is fairly well understood both in magnetic fields which are small with respect to the coercive field, and in very strong fields near saturation, the processes occurring within the major loop have not yet been very well described. When hysteresis depends on the combined action of two variables, such as magnetic field and very high pressure, we know nothing. How are we, for instance, to predict the magnetic state of a submarine cruising at great depth, depending on its diving course?

French scientists, with Pierre Curie, Paul Langevin and Pierre Weiss, played a pioneering role in magnetism. They will certainly have worthy successors, notably in biomagnetism in a broad sense.

This work includes interesting features: exercises with solutions, references fortunately restricted to the best papers and books, and various appendices: lists of

symbols, special functions, properties of various materials, economic aspects, and, last but not least, a very necessary summary of units, which the dual coulombic-amperian presentation made so unnecessarily complicated and unpalatable in the past.

I believe this book should satisfy a broad readership, and be a valuable document to students, researchers, and engineers. I wish it a lot of success.

**Louis NEEL**  
Nobel Laureate in Physics,  
Member of the French Academy of Science

# *PREFACE*

Magnetic materials are all around us, and understanding their properties underlies much of today's engineering efforts. The range of applications in which they are centrally involved includes audio, video and computer technology, telecommunications, automotive sensors, electric motors at all scales, medical imaging, energy supply and transportation, as well as the design of stealthy airplanes.

This book deals with the basic phenomena that govern the magnetic properties of matter, with magnetic materials, and with the applications of magnetism in science, technology and medicine.

It is the collective work of twenty one scientists, most of them from Laboratoire Louis Néel in Grenoble, France. The original version, in French, was edited by Etienne du Trémolet de Lacheisserie, and published in 1999. The present version involves, beyond the translation, many corrections and complements.

This book is meant for students at the undergraduate and graduate levels in physics and engineering, and for practicing engineers and scientists. Most chapters include exercises with solutions.

Although an in-depth understanding of magnetism requires a quantum mechanical approach, a phenomenological description of the mechanisms involved has been deliberately chosen in most chapters in order for the book to be useful to a wide readership. The emphasis is placed, in the part devoted to the atomic aspects of magnetism, on explaining, rather than attempting to calculate, the mechanisms underlying the exchange interaction and magnetocrystalline anisotropy, which lead to magnetic order, hence to useful materials. This theoretical part is placed, in volume I, between a phenomenological part, introducing magnetic effects at the atomic, mesoscopic and macroscopic levels, and a presentation of magneto-caloric, magneto-elastic, magneto-optical and magneto-transport coupling effects. Volume II, dedicated to magnetic materials and applications of magnetism, deals with permanent magnet (hard) materials, magnetically soft materials for low-frequency applications, then for high-frequency electronics, magnetostrictive materials, superconductors, magnetic thin films and multilayers, and ferrofluids. A chapter is dedicated to magnetic recording. The role of magnetism in magnetic resonance imaging (MRI), and in the earth and the life sciences, is discussed. Finally, a chapter deals with instrumentation for magnetic measurements. Appendices provide tables of magnetic properties, unit conversions, useful formulas, and some figures on the economic place of magnetic materials.

We will appreciate constructive comments and indications on errors from readers, via the web site <http://lab-neel.grenoble.cnrs.fr/magnetism-book>

## **ACKNOWLEDGMENTS**

We are grateful for their helpful suggestions to the members of the Reading Committee who worked on the original French edition: V. ARCHAMBAULT (Rhodia-Recherche), E. BURZO (University of Cluj-Napoca, Rumania), I. CAMPBELL (Laboratoire de Physique des Solides, Orsay), F. CLAEYSSEN (CEDRAT, Grenoble), J.M.D. COEY (Trinity College, Dublin), G. COUDERCHON (Imphy Ugine Précision, Imphy), A. FERT (INSA, Toulouse), D. GIVORD (Laboratoire Louis Néel), L. NEEL, Nobel Laureate in Physics (who passed away at the end of 2000), B. RAQUET (INSA, Toulouse), A. RUDI (ECIA, Audincourt), and P. TENAUD (UGIMAG, St-Pierre d'Allevard). The input of many colleagues in Laboratoire Louis Néel or Laboratoire d'Electrotechnique de Grenoble was also invaluable: we are in particular grateful to R. BALLOU, B. CANALS, J. CLEDIERE, O. CUGAT, W. WERNSDORFER. Critical reading of various chapters by A. FONTAINE, R.M. GALERA, P.O. JUBERT, K. MACKAY, C. MEYER, P. MOLLARD, J.P. REBOUILLAT, D. SCHMITT and J. VOIRON helped considerably. Zhang FENG-YUN kindly translated a document from the Chinese, J. TROCCAZ gave helpful advice in biomagnetism, D. FRUCHART, M. HASSLER and P. WOLFERS provided figures, and P. AVERBUCH gave useful advice on the appendix dealing with the economic aspects.

We also would like to thank all our fellow authors for their flawless cooperation in checking the translated version, and often making substantial improvements with respect to the original edition. We are happy to acknowledge the colleagues who, along with the two of us, took part in the translation work: Elisabeth ANNE, Nora DEMPSEY, Ian HEDLEY, Trefor ROBERTS, Ahmet TARI, and Andrew WILLS.

We enjoyed cooperating with Jean BORNAREL, Nicole SAUVAL, Sylvie BORDAGE and Julie RIDARD at Grenoble Sciences, who published the French edition and prepared the present version.

Damien GIGNOUX - Michel SCHLENKER

# *TABLE OF CONTENTS*

## *II - MATERIALS AND APPLICATIONS*

<b>Foreword by Professor Louis Néel</b> .....	XXI
<b>Preface</b> .....	XXIII
<b>Acknowledgements</b> .....	XXIV

### *MAGNETIC MATERIALS AND THEIR APPLICATIONS*

<b>15 - Permanent magnets</b> .....	3
1. Implementation of magnets.....	4
1.1. The two hysteresis loops of a material: magnetization loop M(H) and induction loop B(H) .....	4
1.2. Operation of an ideal permanent magnet within a system .....	4
1.2.1. Load line and working point of a magnet.....	5
1.2.2. Static and dynamic operation of a permanent magnet .....	7
1.2.3. The maximum energy product (static operation).....	8
1.2.4. Free energy involved in the dynamic operation of a magnet.....	10
1.3. Performance parameters of real magnet materials.....	10
1.3.1. Magnetization and induction loops of various hard magnetic materials .....	10
1.3.2. The maximum energy product $(BH)_{\max}$ .....	11
1.3.3. Performance parameters, and their range of variation .....	12
2. Oriented (textured) and isotropic magnets.....	14
2.1. Magnet classification .....	14
2.2. Comparison of the magnetic behavior of oriented and isotropic magnets.....	15
3. Principal industrial magnet materials.....	17
3.1. The various types of sintered and oriented magnets .....	17
3.1.1. AlNiCo magnets .....	18
3.1.2. Ferrite magnets .....	18
3.1.3. Samarium-cobalt magnets .....	18
3.1.4. Neodymium-iron-boron magnets.....	19
3.2. Parameters and typical curves .....	19
3.2.1. Sintered and oriented magnets.....	19
3.2.2. Bonded magnets.....	20
4. Uses of permanent magnets .....	21
4.1. The principal fields of permanent magnet applications.....	21
4.1.1. Miniaturization .....	21
4.1.2. Permanent field sources.....	23
4.1.3. Repelling magnets.....	23
4.2. Properties of industrial magnets.....	24
4.2.1. Principal properties of the AlNiCo magnets.....	24
4.2.2. Main characteristics of ferrite magnets .....	25
4.2.3. Main properties of rare earth magnets .....	26

4.3.	Electromagnetic systems .....	27
4.3.1.	The evolution of motors .....	28
4.3.2.	Permanent magnet actuators.....	29
4.4.	Magnetomechanical systems .....	30
4.4.1.	Magnetic bearings.....	30
4.4.2.	Magnetic couplings.....	31
4.5.	Field sources.....	32
4.5.1.	Sensors .....	32
4.5.2.	Eddy current systems.....	33
4.5.3.	Field source .....	34
4.6.	Modelling permanent magnet systems.....	36
4.6.1.	Closed circuit calculations.....	36
4.6.2.	Open circuit calculations.....	36
4.6.3.	Numerical methods .....	37
4.6.4.	Magnet characteristics.....	39
5.	Magnet materials: microstructure and preparation techniques .....	39
5.1.	Coercivity and how to enhance it .....	39
5.1.1.	Strong uniaxial anisotropy .....	40
5.1.2.	The role of defects and the need for a microstructure.....	40
5.2.	The magnet material must be reduced to fine particles .....	40
5.2.1.	Reduction into grains to suppress nucleation.....	41
5.2.2.	Reduction into grains to increase remanence and the squareness of the M(H) loop..	41
5.3.	General principles of the processes used to prepare magnet microstructures.....	42
5.3.1.	Oriented sintered magnets.....	42
5.3.2.	Coercive powders and bonded magnets .....	44
6.	The basic materials for permanent magnets.....	45
6.1.	Magnetic characteristics of 3d and 4f elements vs the properties required to obtain a hard magnetic material .....	45
6.1.1.	Magnetic moments and exchange interactions in rare earth and transition metals ...	46
6.1.2.	Magnetocrystalline anisotropy of 3d and 4f elements .....	47
6.2.	Transition metal based magnet materials.....	48
6.3.	R-M intermetallic alloys (R = rare earth, M = transition metal).....	51
6.3.1.	R-M exchange coupling, via the d electrons.....	51
6.3.2.	R-M coupling = ferromagnetism or ferrimagnetism .....	55
6.3.3.	Magnetocrystalline anisotropy in R-M compounds with uniaxial crystallographic structure: easy axis or easy plane .....	56
6.4.	Review of intermetallic compounds.....	57
6.4.1.	Binary $R_x M_{1-x}$ compounds .....	58
6.4.2.	Ternary compounds.....	62
6.4.3.	Interstitial ternary compounds .....	63
7.	Magnetization reversal mechanisms.....	64
7.1.	Magnetization reversal in magnetic systems devoid of magnetocrystalline anisotropy: application to AlNiCo magnets.....	64
7.2.	Magnetization reversal in systems with strong magnetocrystalline anisotropy: non-collective reversal in stages.....	66
7.2.1.	Stages of the process.....	66
7.2.2.	The driving forces of reversal: magnetic fields and thermal effects.....	67
7.3.	The magnetization reversal field $H_R$ : relationship with the intrinsic magnetic properties of the principal phase.....	67
7.3.1.	$H_R$ as a function of $H_A$ and local dipolar effects.....	68
7.3.2.	$H_R$ as a function of the energy barrier for the critical mechanism .....	69

7.4. Which mechanism determines magnetization reversal?.....	71
7.4.1. Analysis of the initial magnetization curve, particularly the initial susceptibility ..	71
7.4.2. Observation of domains and domain wall motion in the thermally demagnetised state .....	72
7.4.3. Variation of the reversal field with the direction of the applied field: $H_R(\theta_c)$ .....	73
7.4.4. Modelling of the different mechanisms involved in non-collective magnetization reversal .....	75
Exercises .....	76
Solution to the exercises.....	81
References.....	86
<b>16 - Soft materials for electrical engineering and low frequency electronics.....</b>	<b>89</b>
1. General presentation of soft materials .....	89
1.1. The properties required of a soft material.....	90
1.2. Role of structural and electromagnetic characteristics.....	90
1.2.1. Polarization .....	90
1.2.2. Permeability .....	91
1.2.3. Energy dissipation .....	92
1.3. Energy loss analysis.....	92
1.3.1. Macroscopic aspects.....	92
1.3.2. Calculation of losses in a conductor .....	93
1.4. Losses in rotating or trapezoidal field .....	96
2. Iron based crystalline materials.....	96
2.1. Iron and soft steels .....	96
2.2. Classical iron-silicon alloys.....	97
2.3. Fe-Si sheets with non oriented (NO) grains.....	99
2.3.1. Magnetic characteristics .....	99
2.3.2. Applications.....	100
2.3.3. Evolution and prospects of NO sheets.....	100
2.4. Grain-oriented (GO) Fe-Si sheets.....	101
2.4.1. Domain structure optimization .....	102
2.4.2. Magnetic characteristics .....	103
2.5. Thin iron-silicon sheets.....	104
2.6. High silicon content alloys.....	105
2.6.1. Alloys obtained by fast solidification.....	105
2.6.2. Diffusion enriched alloys.....	107
3. Iron-nickel and iron-cobalt alloys.....	108
3.1. Iron-nickel family .....	108
3.1.1. Alloys around 30% Ni.....	109
3.1.2. Alloys around 50% Ni.....	109
3.1.3. Alloys around 80% Ni (Permalloys).....	110
3.2. Iron-cobalt alloys.....	111
4. Soft ferrites .....	112
4.1. Electromagnetic properties.....	112
4.1.1. Saturation polarization.....	112
4.1.2. Curie temperature .....	112
4.1.3. Anisotropy .....	113
4.1.4. Magnetostriction .....	113
4.1.5. Resistivity .....	113
4.1.6. Permeability - cutoff frequency product .....	113



4.2. Applications of ferrites.....	114
4.2.1. Power electronics.....	114
4.2.2. Low power applications.....	114
5. Amorphous alloys.....	114
5.1. General characteristics.....	115
5.2. Main classes of soft amorphous alloys.....	115
5.2.1. High polarization alloys.....	115
5.2.2. Low magnetostriction alloys.....	116
5.3. Applications of amorphous alloys.....	116
6. Nanocrystalline materials.....	117
6.1. Electromagnetic characteristics.....	118
6.1.1. Polarization.....	118
6.1.2. Anisotropy.....	118
6.1.3. Magnetostriction.....	118
6.1.4. Resistivity.....	119
6.1.5. Uniaxial induced anisotropy.....	119
6.2. Random anisotropy model.....	119
6.3. Applications of nanocrystalline materials.....	121
7. Energy conversion at industrial frequencies (50-400 Hz).....	122
7.1. Distribution transformers.....	123
7.2. Rotating machines.....	127
7.2.1. A refresher on magnetic system energy.....	127
7.2.2. Application to the study of some structures.....	128
7.2.3. The main classes of machines.....	132
7.2.4. Soft magnetic materials used in rotating machines.....	134
8. Actuators.....	134
8.1. An example of a rotating actuator: stepping machine with variable reluctance.....	135
8.2. Choice criteria, orders of magnitude.....	141
9. Energy transformation in power electronics.....	143
9.1. Smoothing inductances, and components for inductive energy storage.....	143
9.2. Requirements associated with high frequency.....	144
9.3. Control-power interfacing.....	146
9.3.1. Maximum pulse length.....	146
9.3.2. Response time.....	146
9.3.3. Comment on the static switch.....	147
Exercises: study of a voltage stabilizing device using a saturable inductance.....	148
Solutions to the exercises.....	151
References.....	153

## 17 - Soft materials for high frequency electronics..... 155

1. Complex susceptibility and permeability.....	155
1.1. Isotropic complex susceptibility and permeability.....	156
1.1.1. Physical meaning of $\chi'$ , $\chi''$ , $\mu'$ and $\mu''$ .....	156
1.1.2. General dynamic regime.....	157
1.1.3. Kramers-Kronig relations.....	158
1.2. Anisotropic materials. Complex susceptibility and permeability tensors.....	158
2. Measuring the complex susceptibility and permeability.....	159
2.1. Internal and external susceptibilities.....	159
2.1.1. External susceptibility in a simple case.....	160
2.1.2. Effect of the demagnetising field on the drifts and losses.....	160
2.1.3. Skin effect and dimensional resonance.....	161