
HANDBOOK OF MODERN FERROMAGNETIC MATERIALS

Alex Goldman, B.S., A.M., Ph.D.
Ferrite Technology Worldwide



Kluwer Academic Publishers
Boston/Dordrecht/London

TABLE OF CONTENTS

Foreword by Takeshi Takei	xv
Preface	xvii
Acknowledgements	xix
Chapter 1-Applications and Functions of Ferromagnetic Material	1
What are Ferromagnetic Materials?	1
History of Ferromagnetic Materials	1
General Categories of Magnetic Materials	2
Applications of Magnetic Materials at DC	4
Power Applications at Low Frequencies	5
Low Frequency Transformers	6
Entertainment Applications	9
High Frequency Power Supplies	11
Microwave Applications	12
Magnetic Recording Applications	13
Miscellaneous Applications	14
Chapter 2-Basics of Magnetism-Source of Magnetic Effect	17
Magnetic Fields	17
Electromagnetism	21
Atomic Magnetism	21
Paramagnetism and Diamagnetism	26
Paramagnetism of Metals	27
Ferromagnetism	29
Magnetic Moments in Ferromagnetic Metals and Alloys	32
Antiferromagnetism	34
Ferrimagnetism	39
Chapter 3-The Magnetization in Domains and Bulk Materials	41
The Nature of Domains	41
Proof of the Existence of Domains	47
The Dynamic Behavior of Domains	47
Bulk Material Magnetization	48
Hysteresis Loops	53
Permeability	54
Magnetocrystalline Anisotropy Constants	55
Magnetostriction	57
Important Properties for Hard Magnetic Materials	57

Chapter 4-AC Properties of Magnetic Materials	59
AC Hysteresis Loops	59
Eddy Current Losses	59
Permeability	62
Disaccommodation	66
Core Loss	68
Microwave Properties	69
Microwave Precessional Modes	71
Logic and Switching Properties of Ferrites	72
Properties of Recording Media	73
Chapter 5-Materials for Permanent Magnet Applications	75
History of Permanent Magnet	75
General Properties of Permanent Magnets	78
Commercial Permanent Magnet Materials-Properties	81
Oxidic or Hard Ferrite Materials	86
Commercial Oriented and Non-Oriented Hard Ferrites	86
Rare-Earth-Cobalt Permanent Magnet Materials	90
Neodymium-Iron-Boron Permanent Magnet Materials	92
Iron-Chromium-Cobalt Magnet Materials	95
Ductile Permanent Magnet Alloys	95
Miscellaneous Permanent Magnet Materials	95
Criteria for Choosing a Permanent Magnet Material	95
Stabilization of Permanent Magnets	100
Cost Considerations in Permanent Magnet Materials	100
Cost of Finished Magnets	101
Calculations and Design of Magnets	102
Optimum Shapes of Ferrite and Metal Magnets	106
Recoil Lines-Operating Load Lines	106
Chapter 6-DC and Low Frequency Applications	107
Material Requirements for DC and Low Frequencies	107
Metallic Materials for DC or Low Frequencies	108
Soft Iron as a Magnetic Material	110
Low Carbon Steels	112
Silicon Steels	115
Iron-based Amorphous Materials	122
Other Low-frequency Magnetic Alloys	127
Nanocrystalline Materials	130
Sintered Soft Iron for Magnetic Applications	130
Chapter 7-Soft Cobalt-Iron Alloys	137
History of Iron-Cobalt Alloys	137
Chemistry and Structure of Cobalt-Iron Alloys	137

TABLE OF CONTENTS

ix

Commercial Availability of Soft Cobalt-Iron Alloys	142
Applications of Soft Cobalt-Iron Alloys	143
Magnetic Components Using Cobalt-Iron Alloys	144
Chapter 8-Metallic Materials for Magnetic Shielding Applications.	145
Shielding Factor and Attenuation	145
Materials for Magnetic Shielding	147
Processing of Shield Materials	149
Measurement of Shield Material	149
Commercial Forms of Supply	151
Shielding Factor as a Function of Frequency	151
Chapter 9-High Permeability-High Frequency Metal Strip	155
History of Nickel-Iron Alloys	156
High Permeability Nickel-Iron Alloys	157
Binary Nickel-Iron Alloys in the 80% Ni Range	158
Nickel-Iron Alloys with 65% Nickel	168
Nickel-Iron Alloys in the 36% Nickel Range	170
Amorphous Materials-High Perm-High Frequency	170
Nanocrystalline Materials-High Frequency Operation	176
Chapter 10-Metal Powder Cores for Telecommunications	183
History of Powder Cores for Telecommunications	184
Iron Powder Cores for Audio and RF Applications	185
Processing of Iron Powder Cores	186
Moly-Perm Powder Cores for Telecommunications	191
Properties of Moly-Perm Powder Cores	196
Chapter 11-Crystal Structure of Ferrites	207
Classes of Crystal Structures in Ferrites	207
Normal Spinel	212
Inverse Spinel	213
Magnetic Moments in Inverse Spinel	213
Mixed Zinc Ferrites	216
Sublattice Magnetizations	217
Hexagonal Ferrites	220
Magnetic Rare-Earth Garnets	222
Miscellaneous Structures	226
Chapter 12-Chemical Aspects of Ferrites	229
Intrinsic and Extrinsic Properties of Ferrites	229
Mixed Ferrites for Property Optimization	230
Permeability Dependence on Chemistry	230

Effect of Iron Content on Permeability	232
Effect of Divalent Ion Variation	236
Permeability Dependence on Zinc	238
Effect of Cobalt on Permeability	239
Oxygen Stoichiometry	240
Effect of Purity on Permeability	244
Effect of Foreign Ions on Permeability	245
Temperature Dependence of Initial Permeability	247
Time Dependence of Permeability (Disaccomodation)	250
Chemistry Dependence of Low Field Losses Loss Factor	251
Tetravalent and Pentavalent Oxide Substitution	251
Losses at High Power Levels	256
Chemistry Considerations for Hard Ferrites	259
Saturation Induction of Microwave Ferrites and Garnets	260
Chemistry Dependence of Microwave Properties	261
Ferrites for Memory and Recording Applications	262

Chapter 13-Microstructural Aspects of Ferrites **265**

Microstructural Engineering for Desired Properties	265
The Effects of Grain Size on Permeability	266
Exaggerated Grain Growth in Ferrites	268
Duplex Grain Structures	271
Effect of Porosity on Permeability	271
Separation of Grain Size and Porosity Effects	273
Effect of Grain Size and Porosity on B-H Loop Parameters	276
Grain Boundary Considerations	279
Early Studies of Grain Boundaries	280
High Frequency Materials	284
Considerations of Microstructure for Microwave Ferrites	291
Microstructural Considerations of Hard Ferrites	292
Resistive and Capacitive Effects in Grain Boundaries	293
Phase Transformation and Oxidation	299

Chapter 14-Ferrite Processing **305**

Powder Preparation-Materials Selection	305
Weighing and Blending	309
Calcining	310
Milling	313
Granulation or Spray Drying	313
Pressing	314
Non-conventional Processing	317
Powder Preparation of Microwave Ferrites	325
Hard Ferrite Powder Preparation	325
Sintering Spinel Ferrites	326
Sintering Manganese-Zinc Ferrites	328

Hold or Soak Temperature and Duration	330
Atmosphere Effects	332
Sintering of MnZn Ferrites for Specific Applications	333
Power Ferrites	335
Microstructural Development	336
Ferrite Kilns	339
Firing of Microwave Ferrites and Garnets	341
Firing of Hard Ferrites	342
Finishing Operations for Ferrites	342
Ferrite and Garnet Films	343
Single Crystal Ferrites	350
Chapter 15-Ferrite Inductors and Transformers for Low Power	361
Inductance	362
Effective Magnetic Parameters	364
Measurement of Effective Permeability	365
Magnetic Considerations:Low Level Applications	366
Pot Core Assembly	370
Pot Core Shapes and Sizes	373
Designing for Inductance in Pot Cores	375
Designing a Pot Core Inductor for Maximum Q	377
Designing Ferrite Inductors for Stability Requirements	378
Flux Density Limitations in Ferrite Inductor Design	379
DC Bias Effects in Ferrite Inductor Design	381
Surface-Mount Design for Pot Cores	381
Low Level Transformers	381
Ferrite Pulse Transformers	385
Ferrites for Low-Level Digital Applications	385
ISDN Components and Materials	387
Multilayer Chip Inductors and LC Filters	389
Chapter 16-Soft Magnetic Materials for EMI Suppression	391
The Need for EMI Suppression Devices	391
Materials for EMI Suppression	396
Frequency Characteristics of EMI Materials	399
Mechanism of EMI Suppression	401
Components for EMI Suppression	402
Common-Mode Filters	403
Differential Mode Filters	407
Metal Powder Cores for EMI Suppression	408
Amorphous-Nanocrystalline Materials for EMI Suppression	420
Chapter 17-Ferrites for Entertainment Applications	425

Ferrite TV Picture Tube Deflection Yokes	425
Materials for Deflection Yokes	427
Flyback Transformers	430
General Purpose Cores for Radio and Television	433
Ferrite Antennas for Radio	434

Chapter 18-Ferrite Transformers and Inductors at High Power 441

The Early Power Applications of Ferrites	441
Power Transformers	442
Frequency-Voltage Considerations	442
Frequency-Loss Considerations	443
The Hysteresis Loop For Power Materials	444
Inverters and Converters	446
Choosing the Right Component for a Power Transformer	453
Permeability Considerations	459
Limitations in Ferrite Design	460
Output Power Considerations	462
Power Ferrites vs Competing Magnetic Materials	465
Power Ferrite Core Structures	465
Low Profile Ferrite Power Cores	467
Surface-Mount Design in Power Ferrites	470
Core Geometries	470
Planar Technology	479
High Frequency Applications	482
Design of Ferrite a Component for Power Transformers	482
Determining the Size of the Core	485
Voltage Regulation in Transformers	490
Other Transformer Design Techniques	492
Magnetic Amplifier-Multi Output Design	496
Power Ferrite Design from Vendor's Catalogs	497
Computer-Aided Power Transformer Design	501
Winding Losses	502
Completing the Design of the Transformer-Winding Data	503
Very High Frequency Power Ferrite Operation	504
Competitive Power Materials for High Frequencies	507
Ferroresonant Transformers	507
Power Inductors	509
Ferrite vs Metallic Power Inductor Materials	510
Flyback Converter Design	521
Swinging Choke	522
Appendices	522

Chapter 19-Materials for Magnetic Recording 535

History of Magnetic Recording	535
-------------------------------	-----

Magnetic Recording Head Properties	541
Audio and Video Magnetic Recording	542
Magnetic Recording Media	543
Magnetic Recording Heads	544
Magnetoresistive Heads	545
Magneto-optic Recording	553
Outlook for Areal Densities in Magnetic Recording	555
Chapter 20-Ferrites for Microwave Applications	559
The Need for Ferrite Microwave Components	559
Ferrite Microwave Components	560
Commercially-Available Microwave Materials	568
Chapter 21-Miscellaneous Magnetic Material Applications	571
Magnetostrictive Transducers	571
Sensors	572
Copier Powders	576
Ferrofluids	576
Electrodes	576
Delay Lines	577
Ferrite Tiles for Anechoic Chambers	577
Reed Switches	580
Chapter 22-Physical-Thermal Aspects of Magnetic Materials	581
Densities of Ferrites	581
Mechanical Properties of Ferrites	581
Thermal Properties	583
Pressure Effects on Ferrites	585
Radiation Resistance	587
Chapter 23-Magnetic Measurements-Materials and Components	589
Measurement of Magnetic Field Strength	589
Measurement of Magnetization	591
Magnetization Curves and Hysteresis Loops	594
Measurements on Hard Ferrites	595
Magnetocrystalline Anisotropy	596
Magnetostriction	597
Inductance and Permeability Measurements	599
Loss Factor	602
Q Factor	602
High Frequency Measurements	602
Permeability Measurements on Ferrite Components	603
Loss Separation at Low Flux Density	607

Losses at High Power Levels-Core Losses	608
Pulse Measurements	615
Amplitude Permeability	615
Bibliography	623
Appendix 1-Abbreviations and Symbols	627
Appendix 2-List of World's Major Ferrite Suppliers	633
Appendix 3-Units conversion from CGS to MKS(SI) System	641
Index	643