
Table of Contents

Symbols	XIX
Acronyms	XXVII
1 Introduction	1
1.1 What are Magnetic Domains?	1
1.2 History of the Domain Concept	2
1.2.1 The Domain Idea	2
1.2.2 Towards an Understanding of Domains	3
1.2.3 Refinements	6
1.3 Micromagnetics and Domain Theory	8
2 Domain Observation Techniques	11
2.1 Introduction	11
2.2 Bitter Patterns	12
2.2.1 General Features	12
2.2.2 Contrast Theory	14
2.2.3 The Importance of Agglomeration Phenomena in Colloids	15
2.2.4 Visible and Invisible Features	18
2.2.5 Special Methods	20
2.2.6 Summary	22
2.3 Magneto-Optical Methods	23
2.3.1 Magneto-Optical Effects	24
2.3.2 The Geometry of the Magneto-Optical Rotation Effects	25
2.3.3 Magneto-Optical Contrast in Kerr Microscopy	28
2.3.4 Interference and Enhancement by Dielectric Coatings	30
2.3.5 Kerr Microscopes	33
2.3.6 The Illumination Path	35

2.3.7	Digital Contrast Enhancement and Image Processing	36
2.3.8	Quantitative Kerr Microscopy	39
2.3.9	Dynamic Domain Imaging	40
2.3.10	Laser Scanning Optical Microscopy	42
2.3.11	Sample Preparation	43
2.3.12	Other Magneto-Optical Effects	44
2.3.13	Summary	48
2.4	Transmission Electron Microscopy (TEM)	49
2.4.1	Fundamentals of Magnetic Contrast in TEM	49
2.4.2	Conventional Lorentz Microscopy	50
2.4.3	Differential Phase Microscopy	54
2.4.4	Electron Holography	56
2.4.5	Special Procedures in Lorentz Microscopy	59
2.4.6	Summary	60
2.5	Electron Reflection and Scattering Methods	61
2.5.1	Overview	61
2.5.2	Type I or Secondary Electron Contrast	62
2.5.3	Type II or Backscattering Contrast	63
2.5.4	Electron Polarization Analysis	67
2.5.5	Other Electron Scattering and Reflection Methods	69
2.5.6	Summary	70
2.6	Mechanical Microscanning Techniques	71
2.6.1	Magnetic Force Microscopy (MFM)	71
2.6.2	Near-Field Optical Scanning Microscopy	78
2.6.3	Other Magnetic Scanning Methods	80
2.7	X-ray, Neutron and Other Methods	81
2.7.1	X-ray Topography of Magnetic Domains	82
2.7.2	Neutron Topography	86
2.7.3	Domain Imaging Based on X-Ray Spectroscopy	86
2.7.4	Magnetotactic Bacteria	89
2.7.5	Domain-Induced Surface Profile	89
2.7.6	Domain Observation in the Bulk?	90
2.8	Integral Methods Supporting Domain Analysis	92
2.9	Comparison of Domain Observation Methods	95
3	Domain Theory	99
3.1	The Purpose of Domain Theory	99
3.2	Energetics of a Ferromagnet	100
3.2.1	Overview	100
3.2.2	Exchange Energy	101
3.2.3	Anisotropy Energy	104
3.2.4	External Field (Zeeman) Energy	109
3.2.5	Stray Field Energy	109
3.2.6	Magneto-Elastic Interactions and Magnetostriction	125
3.2.7	The Micromagnetic Equations	138

3.2.8	Review of the Energy Terms of a Ferromagnet	144
3.3	The Origin of Domains	144
3.3.1	Global Arguments for Large Samples	145
3.3.2	High-Anisotropy Particles	151
3.3.3	Ideally Soft Magnetic Materials	155
3.3.4	The Effect of Anisotropy in Soft Magnetic Materials	165
3.3.5	Résumé: The Absence and Presence of Domains	168
3.4	Phase Theory of Domains in Large Samples	170
3.4.1	Introduction	171
3.4.2	The Fundamental Equations of Phase Theory	171
3.4.3	The Analysis of Cubic Crystals as an Example	178
3.4.4	Field-Induced Critical Points	182
3.4.5	Quasi-Domains	187
3.5	Small Particle Switching	188
3.5.1	Overview	188
3.5.2	Uniform Single-Domain Switching	190
3.5.3	Classifying Switching and Nucleation Processes	193
3.5.4	Classical Solutions	196
3.5.5	Numeric Evaluation in the General Case	198
3.5.6	Continuous Nucleation (Second-Order Transitions)	200
3.6	Domain Walls	201
3.6.1	The Structure and Energy of Infinite Planar Walls	201
3.6.2	Generalized Walls in Uniaxial Materials	212
3.6.3	Walls in Cubic Materials	217
3.6.4	Domain Walls in Thin Films	223
3.6.5	Substructures of Walls—Bloch Lines and Bloch Points	241
3.6.6	Wall Dynamics: Gyrotropic Domain Wall Motion	254
3.6.7	Wall Friction and Disaccommodation-Dominated Motion	264
3.6.8	Eddy-Current-Dominated Wall Motion	268
3.6.9	Résumé: Wall Damping Phenomena and Losses	271
3.7	Theoretical Analysis of Characteristic Domains	273
3.7.1	Flux Collection Schemes on Slightly Misoriented Surfaces	274
3.7.2	Dense Stripe Domains	279
3.7.3	Domains in High-Anisotropy Perpendicular Films	287
3.7.4	Closure Domains	296
3.7.5	Domain Refinement (Domain Branching)	311
3.7.6	The Néel Block as a Classical Example	328
3.8	Résumé	335

4	Material Parameters for Domain Analysis	337
4.1	Intrinsic Material Parameters	337
4.2	Mechanical Measurements	339
4.2.1	Torque Methods	339
4.2.2	Field Gradient Methods	342
4.3	Magnetic Measurements	343
4.3.1	Overview: Methods and Measurable Quantities	343
4.3.2	Magnetometric Methods	344
4.3.3	Inductive Measurements	344
4.3.4	Optical Magnetometers	348
4.3.5	Evaluation of Magnetization Curves	349
4.4	Resonance Experiments	353
4.4.1	Overview: Types of Resonance	353
4.4.2	Theory of Ferromagnetic Resonance	354
4.4.3	Spin Wave Resonance	355
4.4.4	Light Scattering Experiments	356
4.4.5	Wall and Domain Resonance Effects	356
4.5	Magnetostriction Measurements	357
4.5.1	Indirect Magnetostriction Measurements	357
4.5.2	Direct Measurements: General Procedures	358
4.5.3	Techniques of Elongation Measurements	359
4.6	Domain Methods	362
4.6.1	Suitable Domain Patterns	362
4.6.2	Band Domain Width in Bubble Materials	362
4.6.3	Surface Domain Width in Bulk Uniaxial Crystals	364
4.6.4	Internal Stress Measurement by Domain Experiments	365
4.6.5	Stripe Domain Nucleation and Annihilation	365
4.6.6	Domain Wall Experiments in Soft Magnetic Materials	367
4.6.7	Measurements of Domain Wall Dynamics	368
4.7	Thermal Evaluation of the Exchange Constant	368
4.7.1	The Curie Point	369
4.7.2	Molecular Field Theory	369
4.7.3	Low Temperature Variation of Magnetization	370
4.8	Theoretical Guidelines for Material Constants	370
4.8.1	Temperature Dependence of Anisotropy Parameters	370
4.8.2	Mixing Laws for Magnetic Insulators	371
4.8.3	Empirical Rules for Alloy Systems	372
5	Domain Observation and Interpretation	373
5.1	Classification of Materials and Domains	373
5.1.1	Crystal and Magnetic Symmetry	373
5.1.2	Reduced Material Parameters	374
5.1.3	Size, Dimension and Surface Orientation	375
5.1.4	Further Aspects and Synopsis	376
5.2	Bulk High-Anisotropy Uniaxial Materials	378

5.2.1	Branched Domain Patterns	378
5.2.2	Applied Field Effects	383
5.2.3	Polycrystalline Permanent Magnet Materials	386
5.3	Bulk Cubic Crystals	388
5.3.1	Surfaces with Two Easy Axes	388
5.3.2	Crystals with One Easy Axis in the Surface	391
5.3.3	Stress Patterns	395
5.3.4	Slightly Misoriented Surfaces	398
5.3.5	Strong Misorientation	405
5.4	Amorphous and Nanocrystalline Ribbons	410
5.4.1	The As-Quenched State of Amorphous Ribbons	411
5.4.2	Ordered Domain States of Metallic Glasses	413
5.4.3	Wall Studies on Metallic Glasses	419
5.4.4	Domains on Soft-Magnetic Nanocrystalline Ribbons ..	421
5.5	Magnetic Films with Low Anisotropy	422
5.5.1	Overview: Classification of Magnetic Films	422
5.5.2	Thin Films	423
5.5.3	Thick Films with In-Plane Anisotropy	432
5.5.4	Thin and Thick Film Elements	437
5.5.5	Thick Films with Weak Out-of-Plane Anisotropy	450
5.5.6	Cubic Single-Crystal Films and Platelets	454
5.5.7	Double Films	459
5.6	Films with Strong Perpendicular Anisotropy	472
5.6.1	Extended Domain Patterns	472
5.6.2	Localized Domains (Bubbles)	479
5.6.3	Domain Wall Investigations in Perpendicular Films ..	481
5.7	Particles, Needles and Wires	483
5.7.1	Observations on High-Anisotropy Uniaxial Particles ..	483
5.7.2	Very Small Particles	484
5.7.3	Whiskers	488
5.7.4	Magnetic Wires	489
5.8	How Many Different Domain Patterns?	491
6	The Relevance of Domains	493
6.1	Overview	493
6.2	Bulk Soft-Magnetic Materials	494
6.2.1	Electrical Steels	495
6.2.2	High-Permeability Alloys	511
6.2.3	Amorphous and Nanocrystalline Alloys	513
6.2.4	Spinel Ferrites	518
6.3	Permanent Magnets	519
6.3.1	Nucleation-Type Sintered Magnets	521
6.3.2	Pinning-Type Magnets	524
6.3.3	Small-Particle and Nanocrystalline Magnets	525
6.4	Recording Media	530

XVIII Table of Contents

6.4.1	Longitudinal Recording	530
6.4.2	Perpendicular Recording	537
6.4.3	Magneto-Optical Recording	539
6.5	Thin-Film Devices	543
6.5.1	Inductive Thin-Film Heads in Magnetic Recording...	543
6.5.2	Magnetoresistive Sensors	547
6.5.3	Thin-Film Memories	551
6.6	Domain Propagation Devices.....	556
6.6.1	Bubble Memories.....	557
6.6.2	Domain Shift Register Devices	562
6.6.3	Magneto-Optical Display and Sensor Devices	563
6.7	Domains and Hysteresis	564
References		567
Textbooks and Review Articles		641
Name Index		645
Subject Index		673

<http://www.springer.com/978-3-540-64108-7>

Magnetic Domains

The Analysis of Magnetic Microstructures

Hubert, A.; Schäfer, R.

1998, XXIII, 696 p. 1072 illus., 5 illus. in color.,

Hardcover

ISBN: 978-3-540-64108-7