



Time-resolved and three-dimensional characterisation of magnetic states in nanoscale materials in the transmission electron microscope

Teresa Weßels

Schlüsseltechnologien / Key Technologies
Band / Volume 265
ISBN 978-3-95806-685-4

Forschungszentrum Jülich GmbH
Ernst Ruska-Centrum für Mikroskopie und Spektroskopie mit Elektronen (ER-C)
Physik Nanoskaliger Systeme (ER-C-1/PGI-5)

Time-resolved and three-dimensional characterisation of magnetic states in nanoscale materials in the transmission electron microscope

Teresa Weßels

Schriften des Forschungszentrums Jülich
Reihe Schlüsseltechnologien / Key Technologies

Band / Volume 265

ISSN 1866-1807

ISBN 978-3-95806-685-4

Contents

List of Figures	xi
List of Tables	xv
Nomenclature	xvii
1. Introduction	1
2. Magnetism of nanoscale objects	5
2.1. General magnetic concepts	5
2.2. Basis of micromagnetism	7
2.3. Artificial spin ice	10
2.4. Magnetic vortex state	13
2.4.1. Description of a static magnetic vortex state	14
2.4.2. Magnetic vortex core dynamics	15
2.5. Measurement magnetisation dynamics employing X-rays	18
2.6. Summary	21
3. Conventional and magnetic imaging in transmission electron microscopy	23
3.1. Conventional transmission electron microscopy	23
3.1.1. Electron-specimen interactions	23
3.1.2. The transmission electron microscope	25
3.2. Off-axis electron holography	30
3.2.1. Scattering of electrons by electromagnetic fields	30
3.2.2. Reconstruction of phase information	33
3.2.3. Experimental setup	36
3.2.4. Separation of electrostatic and magnetic contributions to the phase	39
3.2.5. Model-based iterative reconstruction of magnetisation	40
3.3. Lorentz microscopy	44
3.4. Time-resolved microscopy	46

3.5. Summary	49
4. Quantitative measurement of virtual antivortices in artificial spin ice	51
4.1. Theoretical background of chiral ice	51
4.2. Sample fabrication	53
4.3. Data analysis	56
4.3.1. Automated detection of particles	58
4.3.2. Removal of a phase ramp in the presence of magnetic stray fields	60
4.3.3. Image distortions and warping of phase images	62
4.3.4. Stitching of multiple phase images	64
4.3.5. Computation of magnetic induction from a known magnetisation distribution	67
4.4. Initial magnetic state of chiral ice	70
4.5. Effect of external magnetic field on chiral ice	74
4.5.1. Magnetic fields required for switching of artificial spin ice pattern	74
4.5.2. Driving mechanism of magnetic reversal of nanomagnets	77
4.6. Detection of virtual antivortices	81
4.6.1. Magnetic state of saturated artificial spin ice	81
4.6.2. Reconstruction of the magnetisation	87
4.6.3. Determination of the three-dimensional magnetic induction from the reconstructed magnetisation	95
4.6.4. Determination of virtual antivortex positions	98
4.6.5. Effect of missing stray fields on the positions of virtual antivortices	102
4.7. Summary	104
5. Magnetic vortices in Py disks	105
5.1. Sample preparation and structure	105
5.2. Reconstruction of the projected in-plane magnetic induction and magnetisation of magnetic vortices	108
5.2.1. Influence of the reference hologram on phase reconstruction	108
5.2.2. Off-axis electron holography of magnetic vortices and reconstruction of the projected in-plane magnetisation . . .	109
5.2.3. Comparison of reconstructed magnetisation with micromagnetic simulations	115
5.2.4. Dependence of core shape on the thickness and diameter of the disk	117

5.3.	Effect of the three-dimensional shape of the disks	119
5.3.1.	Shape variations of the Py disks	119
5.3.2.	Movement of vortex core with sample tilt	121
5.3.3.	Magnetic state of a cross-section	128
5.4.	Summary	130
6.	Dynamic imaging using a fast readout detector in a transmission electron microscope	131
6.1.	Fabrication and expected features of the sample	132
6.2.	Experimental setup for time-resolved microscopy	135
6.2.1.	Overview of general setup	136
6.2.2.	Experimental characterisation of the magnetising holder .	139
6.2.3.	Simulations of electromagnetic fields induced by the RF magnetising holder	145
6.3.	Basics of data analysis: Principal component analysis	148
6.4.	Breathing-like behaviour of the vortex core during its gyration .	150
6.4.1.	Experimental details	150
6.4.2.	Data analysis	152
6.4.3.	Characteristics and consequences of the breathing-like behaviour	155
6.5.	Resonance frequency of magnetic vortex cores	159
6.5.1.	Vortex motion studied by scanning tunnelling X-ray microscopy	160
6.5.2.	Vortex core motion studied by conventional Lorentz microscopy	163
6.5.3.	Time-resolved electron microscopy using a delay line detector	165
6.5.4.	Comparison of the methods	170
6.6.	Limitations of time-resolved microscopy with a delay line detector	172
6.6.1.	Temporal resolution and applicable frequency range . . .	172
6.6.2.	Comparison of different approaches to achieve sub-ns temporal resolution	175
6.7.	Summary	176
7.	Summary and outlook	177
A.	Sample fabrication	183
B.	Data analysis	185
B.1.	Finding unique solutions in model-based iterative reconstruction	185
B.2.	Principal component analysis for noise reduction	187

Contents

B.3. Data analysis for STXM	188
B.4. Energy filter status during DLD experiments	188
B.5. Calibration of DLD images	190
Bibliography	193

Schlüsseltechnologien / Key Technologies
Band / Volume 265
ISBN 978-3-95806-685-4