



Absolute scale off-axis electron holography of thin dichalcogenide crystals at atomic resolution

Florian Winkler

Schlüsseltechnologien / Key Technologies

Band / Volume 191

ISBN 978-3-95806-383-9

Forschungszentrum Jülich GmbH
Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons (ER-C)
Physics of Nanoscale Systems (ER-C-1) / Microstructure Research (PGI-5)

Absolute scale off-axis electron holography of thin dichalcogenide crystals at atomic resolution

Florian Winkler

Schriften des Forschungszentrums Jülich
Reihe Schlüsseltechnologien / Key Technologies

Band / Volume 191

ISSN 1866-1807

ISBN 978-3-95806-383-9

Table of contents

List of figures	xiii
List of tables	xvii
Nomenclature	xix
1 Introduction	1
2 Fundamentals of high-resolution transmission electron microscopy	7
2.1 Setup of a transmission electron microscope	7
2.2 Electron diffraction	9
2.3 Electron optical contrast transfer	12
2.3.1 Image formation in conventional TEM	12
2.3.2 Wave aberrations	14
2.3.3 Resolution limiting effects	17
2.4 Summary	23
3 Off-axis electron holography	25
3.1 Hologram formation and experimental setup	26
3.1.1 Partial coherence	29
3.1.2 Elliptical illumination	32
3.1.3 Influence of the detector	34
3.2 Reconstruction of electron wavefunctions	36
3.2.1 Removal of residual phase modulations in electron wavefunctions	39
3.3 Mean inner potential	42
3.4 Mean free path	44
3.5 Summary	45
4 Two-dimensional materials	47
4.1 Basic properties of transition metal dichalcogenides	48
4.2 TEM sample preparation of 2D materials	51

4.2.1 Transfer setup	52
4.2.2 Elastomer-based dry transfer of 2D materials	53
4.3 Summary	55
5 In situ measurement of electrostatic potentials under applied electrical bias	57
5.1 Design and fabrication of specimens for <i>in situ</i> electrical biasing experiments	58
5.2 Electrostatic potentials in a capacitor	60
5.2.1 Electrostatic potential measurements using electron holography	61
5.2.2 Finite element simulations of electrostatic potentials	68
5.3 Towards an optimized specimen design for <i>in situ</i> electrical biasing experiments	72
5.4 Off-axis electron holography of electrically biased MoS ₂	75
5.4.1 Current-voltage characteristic of suspended MoS ₂	76
5.4.2 Electrostatic potential measurement using electron holography	77
5.5 Summary	80
6 Mean inner potential and thickness measurement of WSe₂	83
6.1 Experiment and simulation details	84
6.1.1 Experimental conditions for off-axis electron holography	84
6.1.2 Simulation of electron wavefunctions	86
6.2 Voronoi tessellation of the WSe ₂ lattice	89
6.3 Local specimen thickness measurement from electron wavefunctions of WSe ₂	92
6.4 Mean inner potential of WSe ₂	97
6.5 Mean free path of WSe ₂	99
6.6 Summary	100
7 Determination of experimental parameters from electron wavefunctions	103
7.1 Strategy for parameter determination	104
7.2 Determination of diffraction-related parameters	107
7.2.1 Uniqueness of the solution and influence of object thickness	111
7.2.2 Influence of parameter values	116
7.2.3 Influence of noise	119
7.2.4 Influence of errors in mean phase and mean amplitude	124
7.2.5 Summary	129
7.3 Determination of imaging-related parameters	129
7.3.1 Uniqueness of the solution	132
7.3.2 Influence of noise	134
7.3.3 Influence of higher order aberrations	141
7.3.4 Summary	144
7.4 Summary	144

8 Absolute scale quantitative off-axis electron holography of WSe₂	147
8.1 Experimental conditions and data preparation	148
8.2 Determination of diffraction-related parameters	151
8.3 Determination and elimination of coherent aberrations	155
8.4 Towards the detection of structural defects	165
8.5 Summary	171
9 Summary	173
Bibliography	175
List of own publications	189
Appendix A Definitions and theorems	191
A.1 Fourier transform	191
A.2 Convolution theorem	191

Schlüsseltechnologien / Key Technologies
Band / Volume 191
ISBN 978-3-95806-383-9