

Superlattices in van der Waals materials: a low-energy electron microscopy study

Jong, T.A. de

Citation

Jong, T. A. de. (2022, November 3). *Superlattices in van der Waals materials: a low-energy electron microscopy study. Casimir PhD Series*. Retrieved from https://hdl.handle.net/1887/3485753

Version:	Publisher's Version
License:	<u>Licence agreement concerning inclusion of doctoral</u> <u>thesis in the Institutional Repository of the University</u> <u>of Leiden</u>
Downloaded from:	https://hdl.handle.net/1887/3485753

Note: To cite this publication please use the final published version (if applicable).

SUPERLATTICES IN VAN DER WAALS MATERIALS

A LOW-ENERGY ELECTRON MICROSCOPY STUDY

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Leiden, op gezag van de rector magnificus prof. dr. ir. H. Bijl, volgens het besluit van het college voor promoties te verdedigen op donderdag 3 november 2022 klokke 15:00 uur

door

Tobias Arie DE JONG

geboren te Leiderdorp, Nederland in 1992 Promotor: Prof. dr. ir. S.J. van der Molen Co-promotor: Prof. dr. ir. R.M. Tromp

Promotiecommissie:

Prof. dr. C. Ropers Prof. dr. ir. H. Zandvliet Dr. S. Conesa-Boj Prof. dr. J. Batenburg Prof. dr. J. van Ruitenbeek Prof. dr. J. Aarts (Georg August Universität Göttingen) (Universiteit Twente) (Technische Universiteit Delft)





Front & Back:An overview showing the wide variety of shapes of stacking domains
occurring in graphene on silicon carbide (Chapter 7).Printed by:Gildeprint – The Netherlands

The research for this thesis was conducted at the Leiden Institute of Physics, Leiden University. This work was financed by the Dutch Research Council (NWO) as part of the Frontiers of Nanoscience programme.

Copyright © 2022 by T.A. de Jong

Casimir PhD Series, Delft-Leiden 2022-20

ISBN 978-90-8593-530-8

An electronic version of this dissertation is available at https://scholarlypublications.universiteitleiden.nl/.

CONTENTS

Su	Summary vii Samenvatting xi		
Sa			
1	Intr	oduction	1
	1.1	Growing 2D materials	3
	1.2	Combining lattices: the Frenkel-Kontorova model	4
	1.3	Charge Density Waves	6
	1.4	Studying domains in van der Waals materials	6
	1.5	Content of this thesis	7
2	Low	Energy Electron Microscopy	11
	2.1	Introduction	12
	2.2	Imaging	12
	2.3	Imaging modes	15
	2.4	LEEM and LEED spectroscopy	16
		2.4.1 Further notes on experiments	17
3	Qua	Intitative analysis of spectroscopic LEEM data	19
	3.1	Introduction	20
	3.2	Detector correction	21
	3.3	High dynamic range spectroscopy	23
		3.3.1 Calibration	24
		3.3.2 Active per-image optimization of MCP bias	25
		3.3.3 Comparison of results	26
	3.4	Drift correction by image registration	26
		3.4.1 Implementation details	29
		3.4.2 Accuracy testing	30
		3.4.3 Time complexity	32
		3.4.4 Discussion	32
	3.5	Dimension reduction	33
		3.5.1 Visualization	35
		3.5.2 Clustering and automatic classification	37
	3.6	Conclusion	38
	3.7	Outlook: Drift correction improvements	39
		3.7.1 GPUs for faster computation	39
		3.7.2 Algorithmic speed improvements	40
		3.7.3 Improvements to accuracy	40

4	Intr	insic stacking domains in graphene on silicon carbide	49
	4.1	Introduction	50
	4.2	Methods	50
		4.2.1 Sample fabrication.	50
		4.2.2 Low-energy electron microscopy	51
		4.2.3 Computations	51
	4.3	Results	52
		4.3.1 Spectroscopy	54
		4.3.2 Domain morphology	55
		4.3.3 Influence on hydrogen de-intercalation	57
	4.4	Conclusion	58
5	On	stacking contrast of low energy electrons in multilayer graphene	63
	5.1	Introduction	64
		5.1.1 Graphene on silicon carbide	64
		5.1.2 Twisted few-layer graphene	65
		5.1.3 Imaging domain boundaries	66
	5.2	Stacking contrast of bilayers in LEEM	67
		5.2.1 Unit cell averaging	68
		5.2.2 Twisted bilayer graphene results	71
		5.2.3 Comparison to strain domain boundaries in graphene on SiC	72
	5.3	Beyond bilayers	76
		5.3.1 2-on-2 graphene layers: phase contrast	78
	5.4	Moiré metrology	79
	5.5	Conclusion	81
	5.6	Outlook: possible computational improvements	82
6	Ima	iging moiré deformation and dynamics in twisted bilayer graphene	87
	6.1	Introduction	88
	6.2	Results	88
		6.2.1 Distortions & Strain	90
		6.2.2 Edge dislocations	92
		6.2.3 High temperature dynamics of the moiré lattice	94
	6.3	Conclusion	95
	6.4	Methods	96
		6.4.1 Sample fabrication.	96
		6.4.2 LEEM	96
		6.4.3 Stitching	97
		6.4.4 Image analysis	97
		6.4.5 Reflectivity calculations	97
		6.4.6 Data & code availability	98
7	Stac	cking domain morphology in epitaxial graphene	103
	7.1	Qualitative description of sample features	105
	7.2	Stripe domains in epitaxial graphene	108
		7.2.1 GPA analysis of strain	110
		7.2.2 Discussion	113

	7.3 7.4 7.5 7.6	Symmetry breaking AA-sites (Spiral domain walls)	115 116 118 118
8	Cha 8.1 8.2 8.3 8.4 8.5 8.6 8.7	arge Density Waves in mixed polytype TaS2 Introduction 8.1.1 Transition metal dichalcogenides 8.1.2 Polytypism 8.1.3 Charge Density Waves 8.1.4 Tantalum disulfide 8.1.5 Towards 2D Sample preparation Pristine 1T-TaS2 Mixed polytypes 8.4.1 Spectra Charge Density Wave states 8.5.1 In-plane CDW domains Discussion 8.6.1 Comparison to low-temperature hidden state	121 122 122 123 124 125 126 127 129 130 132 134 136 139 139
9	Out 9.1 9.2 9.3 9.4	tlook Device scale imaging	143 144 145 145 145 146 146
A	Geo A.1 A.2 A.3 A.4 A.5 A.6	Deformations of a lattice Properties of the deformation. Determination of the displacement field $\mathbf{u}(\mathbf{r})$ Additional notes on choice of reference vectors. Adaptive GPA Decomposition of the displacement field.	149 149 150 151 152 153 154
B	LEE B.1 B.2	E M stitching Considerations	157 160 160
С	Add C.1 C.2 C.3 C.4	litional data of the twisted bilayer graphene sampleAdditional LEEM images/crops	161 162 164 165 168

	C.5 Sample heating	169
D	Additional TaS ₂ figures	171
Ac	cknowledgements	177
Сι	urriculum Vitæ	179
Li	st of Publications	181