eV-TEM: transmission electron microscopy with few-eV electrons

Geelen, D.

Citation

Geelen, D. (2018, May 31). *eV-TEM: transmission electron microscopy with few-eV electrons*. *Casimir PhD Series*. Retrieved from https://hdl.handle.net/1887/63484

Version:	Not Applicable (or Unknown)
License:	[Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden]
Downloaded from:	[https://hdl.handle.net/1887/63484]

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

Cover Page

Universiteit Leiden

Leiden University
Repository

The handle http://hdl.handle.net/1887/63484 holds various files of this Leiden University dissertation.

Author: Geelen, D.
Title: eV-TEM: transmission electron microscopy with few-eV electrons
Issue Date: 2018-05-31

eV-TEM: Transmission Electron Microscopy with few-eV Electrons

PROEFSCHRIFT

ter verkrijging van
de graad van Doctor aan de Universiteit Leiden,
op gezag van Rector Magnificus prof. mr. C.J.J.M. Stolker,
volgens besluit van het College voor Promoties
te verdedigen op donderdag 31 mei 2018
klokke 10:00 uur

door

Daniël Geelen

Geboren te Rotterdam, 21 Augustus 1988

Promotor:
Prof. dr. ir. R.M. Tromp

Co-promotor:
Dr. ir. S.J. van der Molen

Promotiecommisie:
Prof. dr. J.W.M. Frenken (ARCNL)
Dr. I. Müllerová (Czech Academy of Sciences, Praag, Tsjechië)
Prof. dr. E.R. Eliel
Prof. dr. A.J. Koster
Prof. dr. ir. T.H. Oosterkamp

Dit werk maakt deel uit van het onderzoeksprogramma HTSM met projectnummer 12789 dat (mede)gefinancierd is door de Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO).

NWO
Nederlandse Organisatie
voor Wetenschappelijk Onderzoek

The cover of this thesis shows an artist impression of an eV-TEM micrograph of multilayer graphene. On the back an artist impression of the sample holder (left top) and the objective lens (right bottom) is shown.

Typesetting by B. C. van Zuiden using LaTeX.
An electronic version of this thesis can be found at https://openaccess.leidenuniv.nl

Casimir PhD Series, Leiden–Delft, 2018-13.
ISBN 978-90-8593-345-8

Voor Arthur, Liesbeth, en Alexander Geelen.

Contents

1 Introduction 1
- 1.1 The invention of the first electron microscope 2
  - 1.1.1 Better-than-light microscope 2
- 1.2 High-energy electrons 4
- 1.3 Reducing damage 5
- 1.4 Transmission electron microscopy with extremely low-energy electrons 5
- 1.5 Other techniques to study low-energy electron interactions . . 9
- 1.6 What to expect in eV-TEM 10
  - 1.6.1 Quantum-well states 11
  - 1.6.2 Effect of loss processes on LEE reflection and transmission spectra 13
- 1.7 Outline of this thesis 15
- References 18

2 From LEEM to eV-TEM 21
- 2.1 Imaging system 23
  - 2.1.1 Cathode lens 26
  - 2.1.2 Magnetic prism array (MPA) 28
  - 2.1.3 Electron mirror 29
  - 2.1.4 Imaging modes 31
  - 2.1.5 Detector 34
- 2.2 Illumination 35
  - 2.2.1 Reflection (LEEM) 36
  - 2.2.2 Transmission (eV-TEM) 36
- 2.3 Samples 42
  - 2.3.1 Preparation of TEM grids with graphene 43
  - 2.3.2 Si_3N_4 grids 44
  - 2.3.3 Deposition of nanoscale objects on an eV-TEM substrate 46

References 49

3 Microscopy 53
3.1 Imaging graphene with eV-TEM 53
3.2 Imaging nanoscale objects with eV-TEM 59
3.2.1 Gold nanoparticles 59
3.2.2 DNA origami 63
3.3 Resolution of eV-TEM 64
3.4 Outlook 67
References 69

4 Spectroscopy I: Elastic processes 71
4.1 Low-energy electron reflection spectra 72
4.2 Transmission states measured with eV-TEM 74
4.3 Higher energy states 77
4.4 Unoccupied band structure; ARRES 79
4.5 Conclusions and outlook 84
References 86

5 Spectroscopy II: Inelastic processes 89
5.1 Inelastic scattering 90
5.2 Inelastic scattering in ESCHER 92
5.3 Electron energy-loss spectroscopy 92
5.4 Comparing transmission and reflection 94
5.4.1 Mean free paths 96
5.5 Discussion and outlook 101
References 105

6 Catastrophes in Low-Energy Electron Resist Exposures . . . 107
6.1 Low-energy electron exposure of PMMA 109
6.2 Charging model 109
6.2.1 Testing the charging model 114
6.3 Secondary electron emission 118
6.4 Resist changes due to radiation exposure 122
6.5 Summary 127
References 129

Appendices 133
Appendix A Transfer matrices 133
Appendix B Coherence length 138

Appendix C Channel plate calibration for high dynamic range . . 139
Appendix D Data sets obtained with a different electron source . 141
Appendix E Normalization of reflected and transmitted signals . 142

Samenvatting 147

List of publications 151

Curriculum vitæ 153

Acknowledgements 155