



Universiteit
Leiden
The Netherlands

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



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 GEELLEN

GEBOREN TE ROTTERDAM, 21 AUGUSTUS 1988

PROMOTOR:

Prof. dr. ir. R.M. Tromp

CO-PROMOTOR:

Dr. ir. S.J. van der Molen

PROMOTIECOMMISSIE:

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).



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 ₃ N 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 vitae	153
Acknowledgements	155

