

Cambridge University Press  
0521453739 - Reflection High-Energy Electron Diffraction  
Ayahiko Ichimiya and Philip I. Cohen  
Frontmatter  
[More information](#)

---

## REFLECTION HIGH-ENERGY ELECTRON DIFFRACTION

Reflection high-energy electron diffraction (RHEED) is the analytical tool of choice for characterizing thin films during growth by molecular beam epitaxy, since it is very sensitive to surface structure and morphology. However, there has been a need for a book which explains how to analyze RHEED patterns.

This book serves as an introduction to RHEED for beginners and describes detailed experimental and theoretical treatments for experts. First the principles of electron diffraction and many examples of the interpretation of RHEED patterns are described for beginners. The second part contains detailed descriptions of RHEED theory. The third part applies RHEED to the determination of surface structures, gives detailed descriptions of the effects of disorder and critically reviews the mechanisms contributing to RHEED intensity oscillations.

This unified and coherent account will appeal to both graduate students and researchers in the study of molecular beam epitaxial growth.

AYAHIKO ICHIMIYA is Professor in the Department of Quantum Engineering, Nagoya University. His specific areas of research interest are reflection high-energy electron diffraction, crystal growth, surface characterization, positron diffraction and scanning tunneling microscopy.

PHILIP I. COHEN is Professor in the Department of Electrical and Computer Engineering, University of Minnesota. His research interests are mainly in molecular beam epitaxy, electron diffraction, light-assisted film growth and ion-assisted film growth.

Cambridge University Press  
0521453739 - Reflection High-Energy Electron Diffraction  
Ayahiko Ichimiya and Philip I. Cohen  
Frontmatter  
[More information](#)

---

# REFLECTION HIGH-ENERGY ELECTRON DIFFRACTION

AYAHIKO ICHIMIYA AND PHILIP I. COHEN



**CAMBRIDGE**  
UNIVERSITY PRESS

Cambridge University Press  
 0521453739 - Reflection High-Energy Electron Diffraction  
 Ayahiko Ichimiya and Philip I. Cohen  
 Frontmatter  
[More information](#)

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE  
 The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS  
 The Edinburgh Building, Cambridge CB2 2RU, UK  
 40 West 20th Street, New York, NY 10011-4211, USA  
 477 Williamstown Road, Port Melbourne, VIC 3207, Australia  
 Ruiz de Alarcón 13, 28014 Madrid, Spain  
 Dock House, The Waterfront, Cape Town 8001, South Africa  
<http://www.cambridge.org>

© Cambridge University Press 2004

This book is in copyright. Subject to statutory exception  
 and to the provisions of relevant collective licensing agreements,  
 no reproduction of any part may take place without  
 the written permission of Cambridge University Press.

First published 2004

Printed in the United Kingdom at the University Press, Cambridge

*Typeface* Times 10/13 pt.    *System* L<sup>A</sup>T<sub>E</sub>X 2<sub>ε</sub> [TB]

*A catalog record for this book is available from the British Library*

*Library of Congress Cataloging in Publication data*

Ichimiya, Ayahiko, 1940–  
 Reflection high-energy electron diffraction/Ayahiko Ichimiya and Philip I. Cohen.  
 p. cm.

Includes bibliographical references and index.

ISBN 0 521 45373 9

1. Reflection high energy electron diffraction.    2. Thin films – Surfaces – Analysis.

I. Cohen, Philip I.    II. Title.

QC176.84.S93124 2004

530.4'275 – dc22    2004045180

ISBN 0 521 45373 9 hardback

---

The publisher has used its best endeavors to ensure that the URLs for external websites referred to in this book are correct and active at the time of going to press. However, the publisher has no responsibility for the websites and can make no guarantee that a site will remain live or that the content is or will remain appropriate.

---

Cambridge University Press  
0521453739 - Reflection High-Energy Electron Diffraction  
Ayahiko Ichimiya and Philip I. Cohen  
Frontmatter  
[More information](#)

---

To our families, especially our wives, Aoi and Mary.

## Contents

	<i>Preface</i>	<i>page xi</i>
1	Introduction	1
2	Historical survey	3
	2.1 Early experiments	3
	2.2 Molecular beam epitaxy	4
	2.3 Surface studies	7
	2.4 Theories of surface-structure determination	10
3	Instrumentation	12
	3.1 Introduction	12
	3.2 Design of apparatus	13
	3.3 Electron gun design	16
	3.4 Energy filtering	17
4	Wave properties of electrons	19
	4.1 Introduction	19
	4.2 Wavelength and wave vector	19
	4.3 Tangential continuity of the wave vector: refraction	20
	4.4 Plane-wave boundary conditions	23
	4.5 Absorption of the electron beam	25
5	The diffraction conditions	28
	5.1 Crystal lattices	28
	5.2 Key idea of the diffraction	29
	5.3 Miller indices and reciprocal lattices	31
	5.4 Surface lattices	33
	5.5 The Ewald construction	37
	5.6 The zeroth Laue zone: diffraction from rows	40
	5.7 Lattice with a basis	41
6	Geometrical features of the pattern	43
	6.1 Finite two-dimensional sheet: RHEED streaks	43
	6.2 Incoherent scattering	45

viii	<i>Contents</i>	
6.3	Lattice parameter	46
6.4	Vicinal surfaces	49
6.5	Preferred island size	58
7	Kikuchi and resonance patterns	62
7.1	Kikuchi lines	62
7.2	Surface-wave resonances (Kikuchi envelopes)	66
8	Real diffraction patterns	77
8.1	Perfect low-index surfaces	77
8.2	Streak patterns	84
8.3	Ordered islands	88
8.4	Transmission patterns	89
8.5	Rotationally disordered surfaces	97
8.6	Pseudo-one-dimensional crystals	103
8.7	The role of the instrument	107
9	Electron scattering by atoms	113
9.1	Introduction	113
9.2	Elastic scattering: adiabatic approximation	113
9.3	Elastic scattering: Born approximation	114
9.4	Inelastic scattering by atoms	122
10	Kinematic electron diffraction	130
10.1	Introduction	130
10.2	Born approximation	131
10.3	The effect of temperature	148
10.4	Kinematic predictions	150
10.5	Crystal structure factor of a three-dimensional periodic lattice	151
11	Fourier components of the crystal potential	154
11.1	Introduction	154
11.2	Doyle–Turner parametrization	154
11.3	Effect of thermal vibrations	156
11.4	Scattering factors for ionic materials	159
12	Dynamical theory – transfer matrix method	161
12.1	Plan of Chapters 12–14	161
12.2	Introduction	161
12.3	General theory	162
12.4	The transfer matrix	163
12.5	The transfer matrix for a single slice	165
12.6	Multi-slice method	168
12.7	The recursion	169
12.8	Effect of absorption	170
12.9	Relativistic correction	172
13	Dynamical theory – embedded R-matrix method	173
13.1	Introduction	173

	<i>Contents</i>	ix
13.2	Fourier expansion	174
13.3	The wave functions	174
13.4	Multislice method	175
13.5	The recursion	177
13.6	The RHEED intensity	178
13.7	Inelastic damping	179
13.8	Examples	180
14	Dynamical theory – integral method	192
15	Structural analysis of crystal surfaces	195
15.1	Introduction	195
15.2	One-beam condition	196
15.3	Examples of structural analysis	201
16	Inelastic scattering in a crystal	211
16.1	Introduction	211
16.2	One-electron excitation: Yoshioka's theory	211
16.3	Evaluation of the imaginary potential	215
16.4	Plasmon scattering	218
16.5	Thermal diffuse scattering	221
16.6	Absorption coefficients	223
16.7	Analytical form of the imaginary potential	224
16.8	Summary	230
17	Weakly disordered surfaces	234
17.1	Introduction	234
17.2	The main result	238
17.3	A surface with only two layers	240
17.4	Markovian distribution of steps	244
17.5	General Markov results	248
17.6	Vicinal surfaces	248
17.7	Antiphase disorder	253
17.8	Column approximation	257
18	Strongly disordered surfaces	260
18.1	Introduction	260
18.2	Height–difference correlation function	260
18.3	The diffraction profile	262
18.4	Gaussian disorder	266
19	RHEED intensity oscillations	270
19.1	Experimental observations	270
19.2	Kinematic theory	284
19.3	Phenomenological step-density models	290
19.4	Step density with shadowing	293
19.5	Rate-equation models of epitaxy	297
19.6	Phase shift and frequency doubling	301

19.7	Sinusoidal oscillations	305
19.8	Comparisons with scanning probe measurements	308
19.9	Complex oxides	309
19.10	Conclusion	312
Appendix A	Fourier representations	314
Appendix B	Green's functions	318
Appendix C	Kirchhoff's diffraction theory	320
Appendix D	A simple eigenvalue problem	323
Appendix E	Waller and Hartree equation	326
Appendix F	Optimization of dynamical calculation	328
Appendix G	Scattering factor	333
	<i>References</i>	335
	<i>Index</i>	350



## Preface

Reflection high-energy electron diffraction (RHEED) is widely used for surface structural analysis in monitoring epitaxial growth. The purposes of this book are to serve as an introduction to RHEED for beginners and to describe detailed experimental and theoretical treatments for experts. This book consists of three parts. From Chapter 1 to Chapter 8 the principles of electron diffraction and many examples of RHEED patterns are described for beginners. Chapters 9–14 and Chapter 16 give detailed descriptions of RHEED theory. The third part consists of applications of RHEED. In Chapter 15, methods for the determination of atomic structures of surfaces using RHEED are explained with some examples. Chapters 17 and 18 give detailed descriptions of RHEED in the study of surface disordering and epitaxial growth. In Chapter 19 we describe RHEED intensity oscillations for various growth systems.

A. I. expresses many thanks to the late Professor R. Uyeda for his encouragement, to Drs T. Emoto and H. Nakahara for assistance in drawing many figures and to Ms M. Miwa, Ms Y. Mashita, Ms K. Hosono and Ms T. Arakawa for typing the text and checking references and indexes. P. I. C. is grateful to Ms A. D. Cohen for assistance with the references and especially to Drs J. M. Van Hove, C. S. Lent, P. R. Pukite and A. M. Dabiran for their help in understanding diffraction.