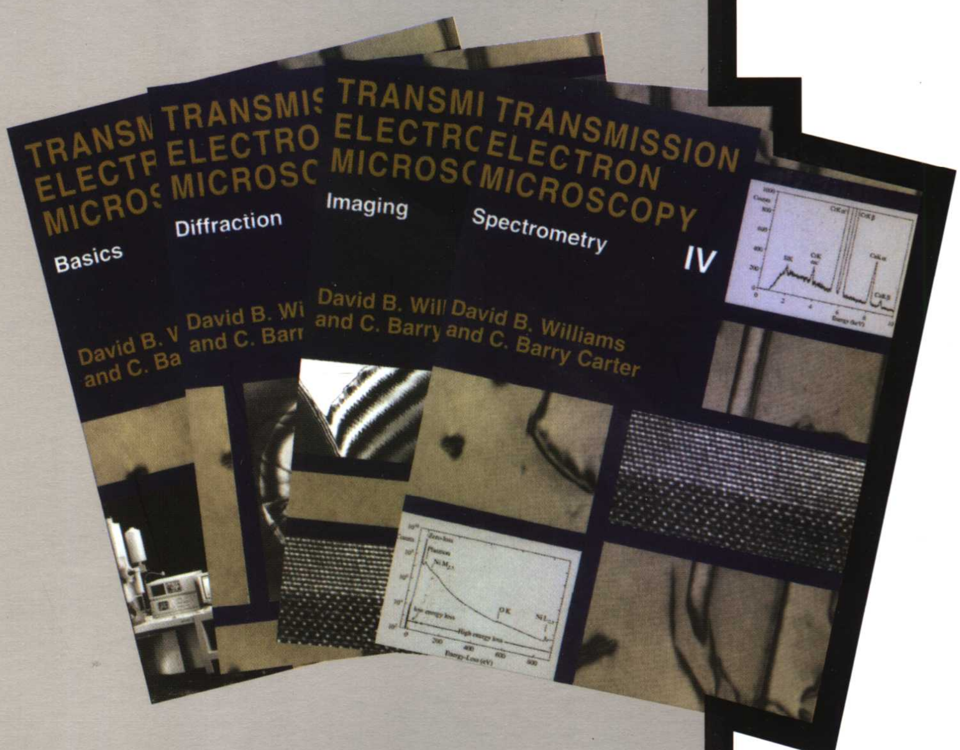
国外大学优秀教材——材料科学与工程系列（影印版）

David B. Williams and C. Barry Carter

透射电子显微学：材料科学教材（4卷本）

Transmission Electron Microscopy: A Textbook for Materials Science



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自从 1897 年汤姆逊发现电子的 35 年之后，诺尔与鲁斯卡发现电子束可以穿过物质并和光一样成像，从而建立了透射电子显微镜的基本原理。利用电子成像的原理，柏林的西门子公司在 1932 年首次生产出第一台透射电子显微镜。

电子显微镜的原理非常相似于光学显微镜，只不过在电子显微镜中，光子由电子取代。因为电子比光子具有更短的波长，电子显微镜的分辨率就可以观察到晶格里的原子。由于电子的透射，它的衍射就可以用来精确地研究物质的结构和成分。正因为透射电子显微镜是材料科学研究中最为重要的分析手段之一，所以“透射电子显微学”是美国大学材料系本科生及研究生院的选修和必修课。这门课往往配合其他电子显微分析技术，如扫描电子显微镜、X-射线等而组成材料分析方法的系列课程。

“透射电子显微学”在全美国的工学院里是材料专业的主修课之一，它也成为其他专业(比如化工、化学、生物、地质、机械、航空、医学)学生的选修课和参考科目，但侧重有所不同。比如对于材料科学与工程专业的学生,教程会较为详细地把重点放在材料的结构分析、衍射理论及各种实验方法等章节上。而对于非材料专业的学生,整个课程会广泛地介绍透射电子显微学在现代科学、工程技术以及生物医用领域内的一般应用,包括陶瓷、玻璃、高分子以及生物材料的电子显微学研究。课时一般为三个学分 (即一周三次课,每课 50 分钟)，其中附带了实验课。

“透射电子显微学”这门课所用的教科书有许多种。 *Transmission Electron Microscopy*（David B. Williams and C. Barry Carter, 1996）是美国最为流行的教科书之一。它分为 4 卷: 基本概念、衍射理论、成像原理和能谱分析。其中第 1 卷主要讲解电子显微镜的基本概念，包括衍射基础知识、显微镜的组成部件、仪器构造与功能，以及样品制备。第 2 卷介绍衍射图像、倒易点阵、衍射电子像的标定，以及各种衍射分析方法。第 3 卷主要是关于成像原理，该卷对材料研究中典型的课题进行系统的介绍。比如晶体缺陷、内应力、相分析等。该卷还着重介绍了高分辨电子显微镜和图像模拟。第 4 卷讨论各种能谱的分析方法与技术，比如 X-射线谱、X-射线定量定性分析、电子能量损失谱、离子能量损失谱等。在透射电子显微学研究中最基本的理论是衍射理论，因而本书利用相当大的篇幅介绍衍射理论以及与其紧密相

关的晶体结构。这些知识是材料学专业的重要基础理论之一。

在当代材料学研究中所遇到的许多关键问题已经不仅仅局限于传统材料，比如陶瓷和金属块材。在21世纪的材料研究中，材料学已经与许多前沿科学紧密联系起来，包括生物材料、纳米材料、医用材料、组织工程等。这些尖端新材料的研究要求实验者不仅懂得基础的衍射理论和实验方法，并且需要发展最新的电子显微镜技术。目前学术界最为重要的课题之一是纳米材料，比如纳米管和纳米组合结构。在许多生物医学和工业工程的应用中，这些纳米颗粒的表面必须经过物理、化学和生物的处理。处理后的纳米颗粒表面结构将会发生本质的变化。而纳米颗粒的表面需要用电子显微镜做各种精确的分析，比如结构、成分、形貌、物性等。这给电子显微学提出了最新的挑战，同时也为其赋予了更为丰富的研究课题。

本书内容新颖，理论完整，例子典型，科目丰富。但是对于本科生与研究生有课时上的限制。所以，各院校可根据专业的特点做适当的取舍。对于偏理科的专业，可以侧重第 2 卷的衍射理论。而对于工程专业，可以选择第 3 卷中的各种成像技术与第 4 卷中的能谱分析方法。在选修本课程之前，应该首先完成普通物理和材料学的基础课程，比如光学、量子物理、晶体结构、金属学、X-射线等。该课应该是本科高年级以及研究生一二年级的课程。

与本课相关的实验课是掌握电子显微技术的必修课。结合该课的理论，学生们必须学习电子显微技术中最为关键的样品制备。与其他材料分析技术相比，透射电子显微镜对样品的制备有极高的要求。而相比之下，扫描电子显微镜、X-射线技术中样品的制备比较简单。透射电子显微学研究中的数据质量在很大程度上往往取决于样品制备的优劣。因此，在透射电子显微学的教学中，对实验方法的掌握成为十分关键的一步。由于透射电子显微学的这个特点，该课程必须要求附带实验课。

正是由于透射电子显微学要求极高的实验经验和专门技术，在美国工学院的教学过程中，这门课大多由电子显微学领域里的专家负责。 该书的两位作者： D. B. Williams and C. B. Carter 博士是世界上电子显微学领域的权威。他们不仅在材料学的研究中有卓越的建树，而且在电子显微技术上有许多原创性的发明。他们在本书里不仅对电子显微学中涉及的基本物理概念有非常精彩的阐述,而且对电子显微学在各种材料中的应用作了极为详尽的描述。更为可贵的是本书引入了大量现代科技最新发展的成果，这为开拓学生眼界,熟悉相关领域动态,掌握现代工业发展有着极为积极的意义。

清华大学出版社在中国工业飞速发展的今天,十分及时地选择 *Transmission Electron*

Microscopy 作为中国大学理工科的材料学主要的英文原版教科书,并引进该书的影印版权，有着非常重要的现实意义。它不仅可以在国内科技英文教学方面作为一个具有国际工程院系的教学标准,也为一般的大专院校和科技单位的研究工作者提供了一本内容丰富、极具科研价值的参考书。我衷心祝愿本书的英文影印版受到国内学生、老师以及科研同行的欢迎,并在教学和科研中起到重大的作用。

时东陆

美国俄亥俄州立辛辛那提大学工学院

材料科学与工程教授

2007 年

Foreword

Electron microscopy has revolutionized our understanding of materials by completing the *processing–structure–properties* links down to atomistic levels. It now is even possible to tailor the microstructure (and mesostructure) of materials to achieve specific sets of properties; the extraordinary abilities of modern transmission electron microscopy—TEM—instruments to provide almost all of the structural, phase, and crystallographic data allow us to accomplish this feat. Therefore, it is obvious that any curriculum in modern materials education must include suitable courses in electron microscopy. It is also essential that suitable texts be available for the preparation of the students and researchers who must carry out electron microscopy properly and quantitatively.

The 40 chapters of this new text by Barry Carter and David Williams (like many of us, well schooled in microscopy at Cambridge and Oxford) do just that. If you want to learn about electron microscopy from specimen preparation (the ultimate limitation); or via the instrument; or how to use TEM correctly to perform imaging, diffraction, and spectroscopy—it's all there! This is, to my knowledge, the only complete text now available that includes all the remarkable advances made in the field of TEM in the past 30 to 40 years. The timing for this book is just right and, personally, it is exciting to have been part of the developments it covers—developments that have impacted so heavily on materials science.

In case there are people out there who still think TEM is just taking pretty pictures to fill up one's bibliography, please stop, pause, take a look at this book, and digest the extraordinary intellectual demands required of the microscopist in order to do the job properly: crystallography, diffraction, image contrast, inelastic scattering events, and spectroscopy. Remember, these used to be fields in themselves. Today, one has to understand the fundamentals of *all* of these areas before one can hope to tackle significant problems in materials science. TEM is a technique of characterizing materials down to the atomic limits. It must be used with care and attention, in many cases involving teams of experts from different venues. The fundamentals are, of course, based in physics, so aspiring materials scientists would be well advised to have prior exposure to, for example, solid-state physics, crystallography, and crystal defects, as well as a basic understanding of materials science, for without the latter how can a person see where TEM can (or may) be put to best use?

So much for the philosophy. This fine new book definitely fills a gap. It provides a sound basis for research workers and graduate students interested in exploring those aspects of structure, especially defects, that control properties. Even undergraduates are now expected (and rightly) to know the basis for electron microscopy, and this book, or appropriate parts of it, can also be utilized for undergraduate curricula in science and engineering.

The authors can be proud of an enormous task, very well done.

G. Thomas
Berkeley, California

Preface

How is this book any different from the many other books that deal with TEM? It has several unique features, but the most distinguishing one, we believe, is that it can really be described as a "textbook"—that is, one designed to be used primarily in the classroom rather than in the research laboratory. We have constructed the book as a series of relatively small chapters (with a few notable exceptions!). The contents of many chapters can be covered in a typical lecture of 50 to 75 minutes. The style is informal for easier reading; it resembles an oral lecture rather than the formal writing you would encounter when reading research papers.

In our experience, the TEM books currently available fall into three major categories. They may be too theoretical for many materials science students; they attempt to cover all kinds of electron microscopy in one volume, which makes it difficult to include sufficient theory on any one technique; or they are limited in the TEM topics they cover. The rapid development of the TEM field has meant that many of the earlier books must automatically be placed in the third category. Although these books are often invaluable in teaching, we have not found them generally suitable as the course textbook in a senior-year undergraduate or first-year graduate course introducing TEM, so we have endeavored to fill this perceived gap.

Since this text is an introduction to the whole subject of TEM, we incorporate *all* aspects of a modern TEM into an integrated whole. So, rather than separating out the broad-beam and convergent-beam aspects of the subject (the traditional structural analysis or imaging versus the "chemical" analysis or "new" techniques), we treat these two aspects as different sides of the same coin. Thus scanning-beam (STEM) imaging is just another way to form an image in a TEM. There is no reason to regard "conventional" bright-field and "conventional" dark-field imaging as any more fundamental ways of imaging the specimen than annular dark-field imaging—or even secondary-electron or STEM *Z*-contrast modes. Similarly, convergent-beam and scanning-beam diffraction are integral parts of electron diffraction, and are complementary to selected-area diffraction. Inelastic electron scattering is the source of both Kikuchi lines and characteristic X-rays. So we don't deliberately split off "conventional" microscopy from "analytical" microscopy.

Our approach is to thread two fundamental questions throughout the text.

Why should we use a particular technique?

How do we put the idea into practice?

We attempt to establish a sound theoretical basis where necessary, although not always giving all the details. We then use this knowledge to build a solid understanding of how we use the instrument. The text is illustrated with examples from across the fields of materials science and engineering and, where possible, a sense of the history of the technique is introduced. We keep references to a minimum and generally accepted concepts are not specifically credited, although numerous classical general references are included.

We both have extensive teaching and research backgrounds in all aspects of TEM comprising diffraction, imaging, and microanalysis. Our research in TEM of materials spans metals, ceramics, composites, and semiconductors. We each bring more than 25 years of TEM experience to the book, and have contributed to the training of a generation of (we hope) skilled electron microscopists. We found that writing the book broadened our own knowledge considerably and was actually fun on some occasions. We hope you experience the same reactions after reading it.

Lastly, we encourage you to send us any comments (positive or negative). We can both be reached by email: dbwl @lehigh.edu and carter@cems.umn.edu

Acknowledgments

We have spent the best part of a decade in the conception and gestation of this text and such an endeavor can't be accomplished in isolation. Our first acknowledgments must be to our wives, Margie and Bryony, and our families, who have borne the brunt of our absences from home (and occasionally the brunt of our presence, also!).

We have both been fortunate to work with other microscopists, post-doctoral associates, and graduate students who have taught us much and contributed significantly to the examples in the text. We would like to thank a few of these colleagues directly: Dave Ackland, Ian Anderson, Charlie Betz, John Bruley, Dov Cohen, Ray Coles, Vinayak Dravid, Joe Goldstein, Brian Hebert, Jason Heffelfinger, John Hunt, Matt Johnson, Vicki Keast, Ron Liu, Charlie Lyman, Stuart McKernan, Joe Michael, Grant Norton, Sundar Ramamurthy, René Rasmussen, Kathy Repa, Al Romig, David A. Smith, Changmo Sung, Caroline Swanson, Ken Vecchio, and Mike Zemyan.

In addition, many other colleagues and friends in the fields of microscopy and microanalysis have helped with the book (even if they weren't aware of it). These include: Ron Anderson, Jim Bentley, Geoff Campbell, Graham Cliff, David Cockayne, the late Chuck Fiori, Peter Goodhew, Ron Gronsky, Peter Hawkes, David Joy, Roar Kilaas, Gordon Lorimer, Harald Müllejans, Dale Newbury, Mike O'Keefe, John Steeds, Peter Swann, Gareth Thomas, Patrick Veyssière, Nestor Zaluzec, and Elmar Zeitler. In addition, many other microscopists kindly provided the figures that we acknowledge individually in the list at the end of the book.

We have received financial support for our microscopy studies through several federal agencies; without this support none of the research that underpins the contents of this book would have been accomplished. In particular, DBW wishes to acknowledge the National Science Foundation (Division of Materials Research) for almost 20 years of continuous funding, the National Aeronautics and Space Administration, the Department of Energy (Basic Energy Sciences), Sandia National Laboratories, and the Materials Research Center at Lehigh, which supports the microscopy laboratory. Portions of the text were written while DBW was on sabbatical or during extended visits to Chalmers University, Göteborg, with Gordon Dunlop and Hans Nordén; the Max Planck Institut für Metallforschung, Stuttgart, with Manfred Rühle; and Los Alamos National Laboratory, with Terry Mitchell. CBC wishes to acknowledge the Department of Energy (Basic Energy Sciences), the National Science Foundation (Division of Materials Research), the Center for Interfacial Engineering at the University of Minnesota, the Materials Science Center at Cornell University, and the SHaRE Program at Oak Ridge National Laboratories. This text was started while CBC was with the Department of Materials Science and Engineering at Cornell University.

Despite our common scientific beginnings as undergraduates in Christ's College, Cambridge, we learned our trade under different microscopists; DBW with Jeff Edington in Cambridge and CBC with Sir Peter Hirsch and Mike Whelan in Oxford. Not surprisingly, the classical texts by these renowned microscopists are referred to throughout this book. They influenced our own views of TEM tremendously, unavoidably contributing to any bias in our opinions, notation, and approach to the whole subject.

List of Acronyms

The field of TEM is a rich source of acronyms, behind which we hide both simple and esoteric concepts. While the generation of new acronyms can be a source of original thinking (e.g., see ALCHEMI), it undoubtedly makes for easier communication in many cases and certainly reduces the length of voluminous textbooks. You have to master this strange language before being accepted into the community of microscopists, so we present a comprehensive listing that you should memorize.

ACF absorption correction factor
A/D analog to digital (converter)
ADF annular dark field
AEM analytical electron microscope/microscopy
AES Auger electron spectrometer/spectroscopy
AFF aberration-free focus
ALCHEMI atom location by channeling-enhanced microanalysis
ANL Argonne National Laboratory
APB anti-phase domain boundary
ASU Arizona State University
ATW atmospheric thin window

BF bright field
BFP back focal plane
BSE backscattered electron
BSED backscattered-electron diffraction
BZB Brillouin-zone boundary

C(1, 2, etc.) condenser (1, 2, etc.) lens
CB coherent bremsstrahlung
CBED convergent-beam electron diffraction
CBIM convergent-beam imaging
CCD charge-coupled device
CCF cross-correlation function
CCM charge-collection microscopy
CDF centered dark field
CF coherent Fresnel/Foucault
CFEG cold field-emission gun
CL cathodoluminescence
CRT cathode-ray tube
CS crystallographic shear
CSL coincident-site lattice

DF dark field
DOS density of states
DP diffraction pattern
DQE detection quantum efficiency
DSTEM dedicated scanning transmission electron microscope/microscopy
DTSA desktop spectrum analyzer

EBIC electron beam-induced current/conductivity
EELS electron energy-loss spectrometry
EFI energy-filtered imaging
ELNES energy-loss near-edge structure
ELP energy-loss program (Gatan)
EMMA electron microscope microanalyzer
EMS electron microscopy image simulation
EPMA electron probe microanalyzer
ESCA electron spectroscopy for chemical analysis
ESI electron spectroscopic imaging
EXAFS extended X-ray absorption fine structure
EXELFS extended energy-loss fine structure

FCF fluorescence correction factor
FEG field-emission gun
FET field-effect transistor
FFT fast Fourier transform

FOLZ first-order Laue zone
FSE fast secondary electron
FTP file transfer protocol
FWHM full width at half maximum
FWTM full width at tenth maximum

GB grain boundary
GCS generalized cross section
GIF Gatan image filter
GOS generalized oscillator strength

HAADF high-angle annular dark field
HOLZ higher-order Laue zone
HPGe high-purity germanium
HRTEM high-resolution transmission electron microscope/microscopy
HV high vacuum
HVEM high voltage electron microscope/microscopy

IDB inversion domain boundary
IEEE International Electronics and Electrical Engineering
IG intrinsic Ge
IVEM intermediate voltage electron microscope/microscopy

K–M Kossel–Möllenstedt

LEED low-energy electron diffraction
LLS linear least-squares
LUT look-up table

MC minimum contrast
MCA multichannel analyzer
MDM minimum detectable mass
MLS multiple least-squares
MMF minimum mass fraction
MSDS material safety data sheets

NCEMSS National Center for Electron Microscopy simulation system
NIH National Institutes of Health
NIST National Institute of Standards and Technology

OR orientation relationship
OTEDP oblique-textured electron diffraction pattern

PB phase boundary
P/B peak-to-background ratio
PEELS parallel electron energy-loss spectrometer/spectrometry
PIMS Precision Ion-Milling System®
PIPS Precision Ion-Polishing System®
PM photomultiplier
POA phase-object approximation

QHRTEM quantitative high-resolution transmission electron microscopy

RB translation boundary (yes, it does!)
RCP rocking-beam channeling patterns
RDF radial distribution function
REM reflection electron microscope/microscopy
RHEED reflection high-energy electron diffraction
RHF relativistic Hartree–Fock
RHFS relativistic Hartree–Fock–Slater

SAD selected-area diffraction
SE secondary electron
SEELS serial electron energy-loss spectrometer/spectrometry
SEM scanning electron microscope/microscopy
SF stacking fault
SHRLI simulated high-resolution lattice images
SIMS secondary ion mass spectrometry
S/N signal-to-noise ratio
SOLZ second-order Laue zone
SRM standard reference material
STEM scanning transmission electron microscope/microscopy
STM scanning tunneling microscope/microscopy

TB twin boundary
TEM transmission electron microscope/microscopy
TMBA too many bloody acronyms

UHV ultrahigh vacuum
UTW ultrathin window

V/F voltage to frequency (converter)
VLM visible-light microscope/microscopy

WB weak beam
WBDF weak-beam dark field
WDS wavelength-dispersive spectrometer/spectrometry
WP whole pattern
WPOA weak-phase object approximation
WWW World Wide Web

XANES X-ray absorption near-edge structure
XEDS X-ray energy-dispersive spectrometer/spectrometry
XRD X-ray diffraction

YBCO yttrium–barium–copper oxide
YAG yttrium–aluminum garnet

ZAF atomic number, absorption, fluorescence (correction)
ZAP zone-axis pattern
ZOLZ zero-order Laue zone

List of Symbols

We use a large number of symbols. Because we are constrained by the limits of our own and the Greek alphabets we often use the same symbol for different terms, which can confuse the unwary. We have tried to be consistent where possible but undoubtedly we have not always succeeded. The following (not totally inclusive) list may help if you remain confused after reading the text.

a relative transition probability
a_0 Bohr radius
a, **b**, **c** lattice vectors
a*, **b***, **c*** reciprocal lattice vectors
A amplitude of scattered beam
A amperes
A absorption correction factor
A active area of the detector
A Richardson's constant
A atomic weight
Å Ångstrom
$\mathcal{A}$ Bloch wave amplitude
$A(\mathbf{U})$ aperture function

b beam-broadening parameter
$\mathbf{b}_e$ edge component of the Burgers vector
$\mathbf{b}_p$ Burgers vector of partial dislocation
$\mathbf{b}_T$ Burgers vector of total dislocation
B beam direction
B magnetic field strength
B background intensity
$B(\mathbf{U})$ aberration function

c velocity of light
C contrast
C composition
C_a astigmatism aberration coefficient
C_c chromatic aberration coefficient
$C_\mathbf{g}$ **g** component of Bloch wave
C_s spherical aberration coefficient
C_X fraction of X atoms on specific sites
C_0 amplitude of direct beam
C_ε combination of the elastic constants
$(C_s\lambda)^{1/2}$ scherzer
$(C_s\lambda^3)^{1/4}$ glaser

d beam (probe) diameter
d diameter of spectrometer entrance aperture
d spacing of moiré fringes
d interplanar spacing
d_c effective source size
d_d diffraction-limited beam diameter
d_g Gaussian beam diameter
$d_{hk\ell}$ $hk\ell$ interplanar spacing
d_{im} smallest resolvable image distance
d_{ob} smallest resolvable object distance
d_s spherical-aberration limited beam diameter
d_{eff} effective entrance aperture diameter at recording plane
dz thickness of a diffracting slice
$d\sigma/d\Omega$ differential cross section of one atom
D change in focus
D distance from projector crossover to recording plane
D electron dose
D_{im} depth of focus
D_{ob} depth of field
D_1, D_2 tie-line points on dispersion surfaces in presence of defect

e charge on the electron
E energy
$\mathbf{E}$ electric field
E Young's modulus
E_a spatial coherence envelope
E_c chromatic aberration envelope
E_c critical ionization energy
E_d displacement energy
E_K ionization energy for K-shell electron
E_L ionization energy for L-shell electron
$\mathcal{E}$ total energy
$\mathcal{E}$ energy loss
$\mathcal{E}_m$ average energy loss
$\mathcal{E}_P$ plasmon energy loss
E_P plasmon energy
E_t threshold energy
E_0 beam energy
$E(\mathbf{U})$ envelope function
$E_c(\mathbf{u})$ envelope function for chromatic aberration
$E_d(\mathbf{u})$ envelope function for specimen drift
$E_D(\mathbf{u})$ envelope function for the detector
$E_s(\mathbf{u})$ envelope function for the source
$E_v(\mathbf{u})$ envelope function for specimen vibration

f focal length
$f(\mathbf{r})$ strength of object at point x,y
$f(\theta)$ atomic scattering factor/amplitude
f_x scattering factor for X-rays
$f_i(x)$ residual of least-squares fit
F Fano factor
F fluorescence correction factor
$\mathbf{F}$ Lorentz force
F_B fraction of B alloying element
F_g special value of $F(\theta)$ when θ is the Bragg angle
$F(P)$ Fourier transform of plasmon intensity
$F(\mathbf{u})$ Fourier transform of $f(\mathbf{r})$
$F(0)$ Fourier transform of elastic intensity
$F(1)$ Fourier transform of single-scattering intensity
$F(\theta)$ structure factor

$\mathbf{g}$ diffraction vector (magnitude of $\mathbf{K}$ at the Bragg angle)
$g(\mathbf{r})$ intensity of image at point (x,y)
G Bragg reflection
G radius of a HOLZ ring
G giga
$G(\mathbf{u})$ Fourier transform of g($\mathbf{r}$)

h Planck's constant
h distance from specimen to the aperture
h(r) contrast transfer function
$(hk\ell)$ Miller indices of a crystal plane
$hk\ell$ indices of diffraction spots from $hk\ell$ plane

H spacing of the reciprocal-lattice planes parallel to the electron beam
$H(\mathbf{u})$ Fourier transform of $h(\mathbf{r})$

I intensity
I intrinsic line width of the detector
i_e emission current
i_f filament heating current
I_g intensity in the diffracted beam
I_K K-shell intensity above background
$I(\mathbf{k})$ kinematical intensity
I_P intensity in the first plasmon peak
I_T total transmitted intensity
I_0 intensity in the zero-loss peak
$I_\mathbf{0}$ intensity in the direct beam
$I(\ell)$ low-loss spectrum intensity

J current density

k magnitude of the wave vector
k Boltzmann's constant
k kilo
$\mathbf{k}_I$ $\mathbf{k}$-vector of the incident wave
$\mathbf{k}_D$ $\mathbf{k}$-vector of the diffracted wave
k_{AB} Cliff–Lorimer factor
K bulk modulus
K Kelvin
K Kramers constant
K sensitivity factor
K inner core shell/characteristic X-ray line/ionization edge
$\mathbf{K}$ change in $\mathbf{k}$ due to diffraction
$\mathbf{K}_B$ magnitude of $\mathbf{K}$ at the Bragg angle
K_o kernel

L camera length

m number of focal increments
m_0 rest mass of the electron
M magnification
M mega
M_A angular magnification
M_T transverse magnification
M_1, M_2 tie-line points on dispersion surfaces

n integer
n free-electron density
n nano
$\mathbf{n}$ vector normal to the surface
n_s number of electrons in the ionized subshell
N noise
N number of counts
N number of atoms per unit area
N $h + k + \ell$

$N(E)$ number of bremsstrahlung photons of energy E
N_0 Avogadro's number

O direct beam

p pico
p momentum
p integer
P peak intensity
P FWHM of a randomized electronic pulse generator
P_K probability of K-shell ionization
$P(z)$ scattering matrix for a slice of thickness z

Q number of scattering events per unit distance
Q cross section

r radius
r distance a wave propagates
r power term to fit background in EELS spectrum
r_M image translation distance
$\mathbf{r}_n$ lattice vector
$\mathbf{r}^*$ reciprocal lattice vector
r_{ast} astigmatism disk radius
r_{chr} chromatic-aberration disk radius
r_{sph} spherical-aberration disk radius
r_{min} minimum disk radius
r_{th} theoretical disk radius
$\mathbf{r}'_n$ lattice vector in strained crystal
r_0 maximum radius of DP in focal plane of spectrometer
$\mathbf{R}$ crystal lattice vector
R count rate
R resolution of XEDS detector
R distance on screen between diffraction spots
$\mathbf{R}_n$ lattice displacement vector

s excitation error or deviation parameter
$\mathbf{s}_\mathbf{R}$ excitation error due to defect
$\mathbf{s}_z$ ($\mathbf{s}_g$) excitation error in the z direction
s_{eff} effective excitation error
S distance from the specimen to detector
S signal
S standard deviation for n measurements
sr steradians

t shift vector between the ZOLZ and the HOLZ
t' absorption path length
$T(\mathbf{u})$ objective-lens transfer function
$T_{eff}(\mathbf{u})$ effective transfer function

u object distance
u unit vector along the dislocation line
$\mathbf{u}^*$ vector normal to the ZOLZ
u_k displacement field
U overvoltage
U_g Fourier component of the perfect-crystal potential

v image distance
v velocity of an electron
V accelerating voltage
$\mathcal{V}$ potential energy
V_c the volume of the unit cell
V_c inner potential of cavity
V_t projected potential through the thickness of the specimen
$V(\mathbf{r})$ crystal inner potential

T absolute temperature
T Tesla
T_C period of rotation

(UVW) indices of a crystal direction
UVW indices of beam direction

w $s\xi_g$ (excitation error × extinction distance)

× times
x distance
× times (magnification)
x, y, z atom coordinates
X FWHM due to detector

y parallax shift in the image
y displacement at the specimen

z specimen height (distance along the optic axis)
Z atomic number/atomic number correction factor

Greek symbols

α phase shift due to defect
α semiangle of incidence/convergence
α X-ray take-off angle
α_{opt} optimum convergence semiangle

β brightness
β ratio of electron velocity to light velocity
β semiangle of collection
β_{opt} optimum collection semiangle

γ degree of spatial coherence
γ phase of direct beam

Δ change/difference
Δ width of energy window
$\Delta\phi$ phase difference
$\Delta\theta_i$ angles between Kossel–Möllenstedt fringes
Δ_{AB} difference in mass-absorption coefficients
ΔE energy spread
$\Delta\mathcal{E}_P$ plasmon line width
Δf maximum difference in focus
Δf_{AFF} aberration-free (de)focus
Δf_{MC} minimum contrast defocus
Δf_{opt} optimum defocus

Δf_{sch} Scherzer defocus
Δh relative depth in specimen
ΔI change in intensity
Δp parallax shift
ΔV change in the inner potential
Δx path difference
Δx half-width of image of undissociated screw dislocation
Δx_{res} resolution at Scherzer defocus
Δz change in height
δ angle between detector normal and line from detector to specimen
δ diameter of disk image
δ diffuseness of interface
δ fluorescence enhancement ratio
δ precipitate/matrix misfit

ε angle of deflection
ε detector efficiency
ε energy to create an electron–hole pair
ε strain
ε_0 permittivity of free space (dielectric constant)

$\eta(\theta)$ phase of the atomic scattering factor
η phase change
ν Poisson's ratio

Φ work function
$\Phi_A^{\Delta\rho t}$ X-ray emission from element A in an isolated thin film
ϕ angle between Kikuchi line and diffraction spot
ϕ angle between two Kikuchi line pairs
ϕ angle between two planes
ϕ angle of tilt between stereo images
ϕ phase of a wave
ϕ^* complex conjugate of ϕ
ϕ_g amplitude of the diffracted beam
ϕ_0 amplitude of the direct beam
ϕ_x angle of deflection of the beam
$\phi(\rho t)$ depth distribution of X-ray production

χ wave vector outside the specimen
χ_G wave vector which terminates on the point G in reciprocal space
χ_O wave vector which terminates on the point O in reciprocal space
$\chi(\mathbf{u})$ phase-distortion function

κ thermal conductivity

ξ_g extinction distance for diffracted beam
ξ_g' absorption parameter
ξ_0 extinction distance for direct beam
ξ_g^{abs} absorption-modified ξ_g

λ mean-free path
λ wavelength
λ_c coherence length
λ_P plasmon mean free path
λ^{-1} radius of Ewald sphere

μ micro
μ refractive index
μ/ρ mass absorption coefficient
$\mu^{(j)}(\mathbf{r})$ Bloch function

ν frequency

ψ amplitude of a wave
ψ^T total wave function
ψ^{tot} total wave function

ρ angle between directions
ρ density
ρ_c information limit due to chromatic aberration
$\rho(\mathbf{r})$ radial distribution function
ρt mass thickness
ρ_i^2 area of a pixel

σ scattering cross section of one atom
σ standard deviation
σ stress
σ_K ionization cross section for K-shell electron
σ_T total scattering cross section
$\sigma_K(\beta\Delta)$ partial ionization cross section

θ scattering semiangle
θ_B Bragg angle
θ_C cut-off semiangle
θ_E characteristic scattering semiangle
θ_0 screening parameter

τ detector time constant
τ dwell time

ω fluorescence yield
ω_c cyclotron frequency
ω_p plasmon frequency
Ω solid angle of collection

$\otimes$ convolution (multiply and integrate)

Contents