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PREFACE

This volume contains two substantial contributions, on the use of the cathodoluminescent signal in scanning electron microscopy and on fuzzy transforms.

The first chapter fills a serious gap in the literature for, although cathodoluminescence is discussed in all the books on scanning electron microscopy, there has been no recent account of the physics of the phenomenon and of the associated instrumentation. C.M. Parish and P.E. Russell take us through the basic physics and explain what types of signal can be captured, after which they present the types of accessory needed for spectral imaging and pulsed operation, as well as the more standard detectors. The most active research areas are then summarized, and the use of cathodoluminescence in the scanning transmission electron microscope is evoked.

In the second contribution, I. Perfilieva, to whom we owe many original ideas in fuzzy set theory, discusses the difficult topic of fuzzy transforms. After explaining the basic mathematical tools (semirings and semimodules), she describes semilinear spaces and introduces the required function spaces. This brings us to the real subject of the review, fuzzy transforms. These are analyzed in great detail, and the paper concludes with a good variety of applications

Once again, I thank all the authors for contributing to the series and for the trouble they have taken to make their material accessible to a wide readership. Forthcoming contributions are listed in the following pages.

Peter W. Hawkes

FUTURE CONTRIBUTIONS

S. Ando
Gradient operators and edge and corner detection

P. Batson (special volume on aberration-corrected electron microscopy)
Some applications of aberration-corrected electron microscopy

C. Beeli
Structure and microscopy of quasicrystals

V.T. Binh and V. Semet (vol. 148)
Planar cold cathodes

A.B. Bleloch (special volume on aberration-corrected electron microscopy)
Aberration correction and the SuperSTEM project

C. Bontus and T. Köhler
Helical cone-beam tomography

G. Borgefors
Distance transforms

Z. Bouchal
Non-diffracting optical beams

A. Buchau
Boundary element or integral equation methods for static and time-dependent problems

B. Buchberger
Gröbner bases

F. Colonna and G. Easley
The generalized discrete Radon transforms and their use in the ridgelet transform

T. Cremer
Neutron microscopy

A.X. Falcão
The image foresting transform

R.G. Forbes
Liquid metal ion sources

C. Fredembach
Eigenregions for image classification

A. Gölzhäuser
Recent advances in electron holography with point sources

D. Greenfield and M. Monastyrskii
Selected problems of computational charged particle optics

M. Haider (special volume on aberration-corrected electron microscopy)
Aberration correction in electron microscopy

M.I. Herrera
The development of electron microscopy in Spain

N.S.T. Hirata
Stack filter design

M. Hÿtch, E. Snoeck and F. Houdellier (special volume on aberration-corrected electron microscopy)
Aberration correction in practice

K. Ishizuka
Contrast transfer and crystal images

J. Isenberg
Imaging IR-techniques for the characterization of solar cells

A. Jacobo
Intracavity type II second-harmonic generation for image processing

K. Jensen (vol. 149)
Field-emission source mechanisms

B. Kabius (special volume on aberration-corrected electron microscopy)
Aberration-corrected electron microscopes and the TEAM project

L. Kipp
Photon sieves

A. Kirkland and P.D. Nellist (special volume on aberration-corrected electron microscopy)
Aberration-corrected electron micrsocpy

G. Kögel
Positron microscopy

T. Kohashi
Spin-polarized scanning electron microscopy

O.L. Krivanek (special volume on aberration-corrected electron microscopy)
Aberration correction and STEM

R. Leitgeb
Fourier domain and time domain optical coherence tomography

B. Lencová
Modern developments in electron optical calculations

H. Lichte (vol. 150)
New developments in electron holography

W. Lodwick (vol. 148)
Interval and fuzzy analysis: a unified approach

L. Macaire, N. Vandenbroucke and J.-G. Postaire
Color spaces and segmentation

M. Matsuya
Calculation of aberration coefficients using Lie algebra

S. McVitie
Microscopy of magnetic specimens

F. Meyer and C. Vachier (vol. 148)
On the regularization of the watershed transform

S. Morfu and P. Marquié
Nonlinear systems for image processing

T. Nitta
Back-propagation and complex-valued neurons

M.A. O'Keefe
Electron image simulation

D. Oulton and H. Owens
Colorimetric imaging

N. Papamarkos and A. Kesidis
The inverse Hough transform

R.F.W. Pease (vol. 150)
Miniaturization

K.S. Pedersen, A. Lee and M. Nielsen
The scale-space properties of natural images

S.J. Pennycook (special volume on aberration-corrected electron microscopy)
Some applications of aberration-corrected electron microscopy

E. Plies (special volume on aberration-corrected electron microscopy)
Electron monochromators

V. Randle
Electron back-scatter diffraction

E. Rau
Energy analysers for electron microscopes

E. Recami
Superluminal solutions to wave equations

J. Rodenburg
Ptychography and related diffractive imaging methods

H. Rose (special volume on aberration-corrected electron microscopy)
The history of aberration correction in electron microscopy

G. Schmahl
X-ray microscopy

J. Serra (vol. 150)
New aspects of mathematical morphology

R. Shimizu, T. Ikuta and Y. Takai
Defocus image modulation processing in real time

S. Shirai
CRT gun design methods

T. Soma
Focus-deflection systems and their applications

J.-L. Starck
Independent component analysis: the sparsity revolution

I. Talmon
Study of complex fluids by transmission electron microscopy

N. Tanaka (special volume on aberration-corrected electron microscopy)
Aberration-corrected microscopy in Japan

G. Teschke and I. Daubechies
Image restoration and wavelets

M.E. Testorf and M. Fiddy
Imaging from scattered electromagnetic fields, investigations into an unsolved problem

N.M. Towghi
I_p norm optimal filters

E. Twerdowski
Defocused acoustic transmission microscopy

Y. Uchikawa
Electron gun optics

K. Urban and J. Mayer (special volume on aberration-corrected electron microscopy)
Aberration correction in practice

K. Vaeth and G. Rajeswaran
Organic light-emitting arrays

M. van Droogenbroeck and M. Buckley
Anchors in mathematical morphology

R. Withers
Disorder, structured diffuse scattering and local crystal chemistry

Y. Zhu (special volume on aberration-corrected electron microscopy)
Some applications of aberration-corrected electron microscopy

CONTENTS

ADVANCES IN IMAGING AND ELECTRON PHYSICS, VOL. 147

Scanning Cathodoluminescence Microscopy

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I. Introduction

A. What Is Cathodoluminescence?

Cathodoluminescence (CL) is light emitted by a solid material due to irradiation by an electron beam, which is typically in the energy range of several hundred electron volts to several hundred kiloelectron volts. When the spectral distribution of light is studied, CL spectroscopy is performed. When the intensity of light emission is mapped in space, this is termed *CL microscopy*. The most common and versatile way to perform CL experiments is with a scanning electron microscope (SEM) that has been specially equipped with some form of light collection and detection apparatus. It is also possible to perform CL with an optical microscope equipped with an electron flood gun. CL spectroscopy can also be performed in a nonimaging mode in a vacuum chamber equipped with an electron source and an optical spectrometer. In recent years, the performance of CL microscopy and spectroscopy in a scanning transmission electron microscope (STEM) has grown in popularity. This review emphasizes SEM-CL and briefly discusses STEM-CL.

CL is a valuable technique for studying the optical emission properties of semiconductor and insulating materials at a very fine spatial resolution. Changes in CL spectra with processing or service can lead to information about the formation of defect states or the change in defect populations. CL microscopy allows locations of defects or features to be mapped with resolution that can approach tens of nanometers. CL is an indispensable tool for the study of light emission from materials and the factors that improve or degrade it in the semiconductor and optoelectronic industries. CL is also heavily used in studies of mineralogy and geology.

This review attempts to cover advances in CL instrumentation, theory, and application. A number of excellent reviews of CL or of luminescence experiments in general have been published (Bajaj, 2001; Gustafsson, 2006; Gustafsson *et al.*, 1998; Herman *et al.*, 1991; Newbury *et al.*, 1986; Phillips, 2006; Yacobi and Holt, 1986, 1990). As such, the emphasis here is on advances published in the past several years, although important articles or references published less recently also are discussed.

We begin by discussing the basic physics that gives rise to the CL signal and how the nature of the solid material under investigation changes the CL response. Brief discussions of experimental considerations for performing CL in the SEM and experimental techniques that complement CL follow. A number of different types of CL experiments can be performed, and strategies for performing these experiments are presented, followed by a review of advances in SEM-CL instrumentation and theory.

After a discussion of the advances in instrumentation and theory, the review moves to fields of active CL research, such as gallium nitride–based optoelectronic materials and photovoltaic materials. Then, the use of CL as a probe of nonoptical properties of materials is reviewed. Finally, STEM-CL is discussed, followed by a summary and conclusions.

B. Carrier Generation and Motion

CL and related techniques, such as photoluminescence or electron beam–induced current, are predicated on the creation of electron–hole pairs (EHPs) within the sample being investigated. The beam of a scanning electron microscope is ideal for this purpose (Newbury *et al.*, 1986; Yacobi and Holt, 1990). The impact of an SEM primary beam electron with typical energies of 100 eV to 30 keV with a nonmetallic sample results in many different inelastic scattering processes as the beam electron loses energy in the solid (Goldstein *et al.*, 2003; Newbury, 1986). The beam electrons have sufficient energy to promote electrons (e^-) from the valence band (VB) of the solid into the conduction band (CB), which leaves behind holes (h^+) in the VB. Thus, an EHP is formed, as shown in Figure 1.

As the beam electron scatters through the solid, it continually loses energy. It has been found empirically (Klein, 1968; Newbury *et al.*, 1986; Yacobi and Holt, 1990) that the average amount of energy lost per EHP generated (E_{EHP}) is $\approx 3\ E_{GAP}$, where E_{GAP} is the bandgap of the material. The experimental data from which these $E_{EHP} \approx 3\ E_{GAP}$ data are derived are shown as Figure 2. Thus, a single beam electron produces many EHPs within the sample. For example, a 1-keV electron incident on gallium nitride (GaN), which has $E_{GAP} \approx 3.3$ eV ($E_{EHP} \approx 10$ eV), would be expected to produce an average

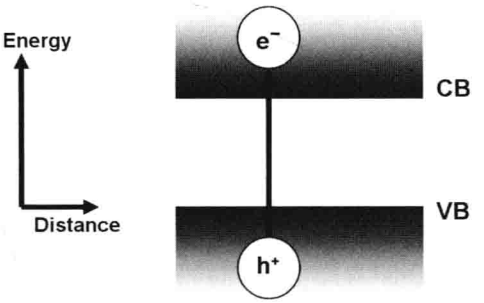

FIGURE 1. Schematic illustration of EHP generation. CB, Conduction band; VB, valence band. (From Parish, 2006.)

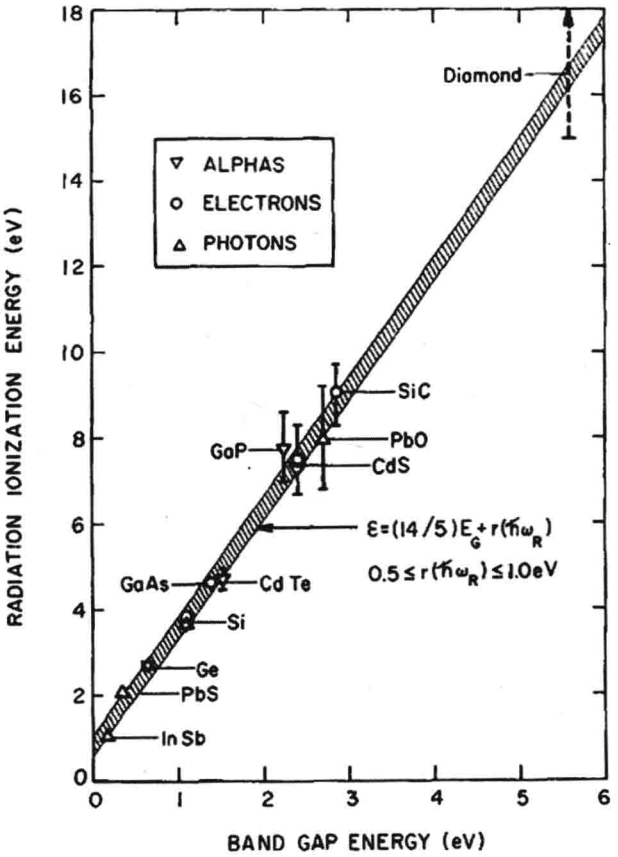

FIGURE 2. Experimental data indicating the approximate $E_{EHP} \approx 3E_{GAP}$ relation. (Reprinted with permission from Klein, 1968.) © 1968 American Institute of Physics.

of 100 EHPs before exhausting its incident energy. Quantitatively, the actual number of EHPs produced is less than this limit, as backscattered electrons do not necessarily deposit all of their incident energy into the sample. The rate of EHP generation, expressed in EHPs generated per second, can be expressed as shown in Eq. (1):

$$g_0 = \frac{E_0(1-n)i_b}{E_{EHP}q}. \tag{1}$$

Here, E_0 is the SEM beam energy, E_{EHP} is the energy per EHP creation, i_b is the SEM beam current, q is the elementary electronic charge (1.6×10^{-19} C), and $(1 - n)$ is a factor to account for the energy lost