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*CEMES-CNRS
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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

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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

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Non-diffracting optical beams

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

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The image foresting transform

R.G. Forbes

Liquid metal ion sources

C. Fredembach

Eigenregions for image classification

A. Götzhäuser

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J. Isenberg

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A. Jacobo

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Aberration-corrected electron microscopy

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T. Kohashi
Spin-polarized scanning electron microscopy

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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 $\approx 3 E_{\text{GAP}}$, where E_{GAP} is the bandgap of the material. The experimental data from which these $E_{\text{EHP}} \approx 3 E_{\text{GAP}}$ 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 $E_{\text{GAP}} \approx 3.3$ eV ($E_{\text{EHP}} \approx 10$ eV), would be expected to produce an average

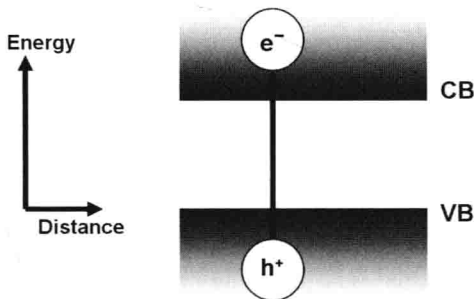


FIGURE 1. Schematic illustration of EHP generation. CB, Conduction band; VB, valence band. (From Parish, 2006.)

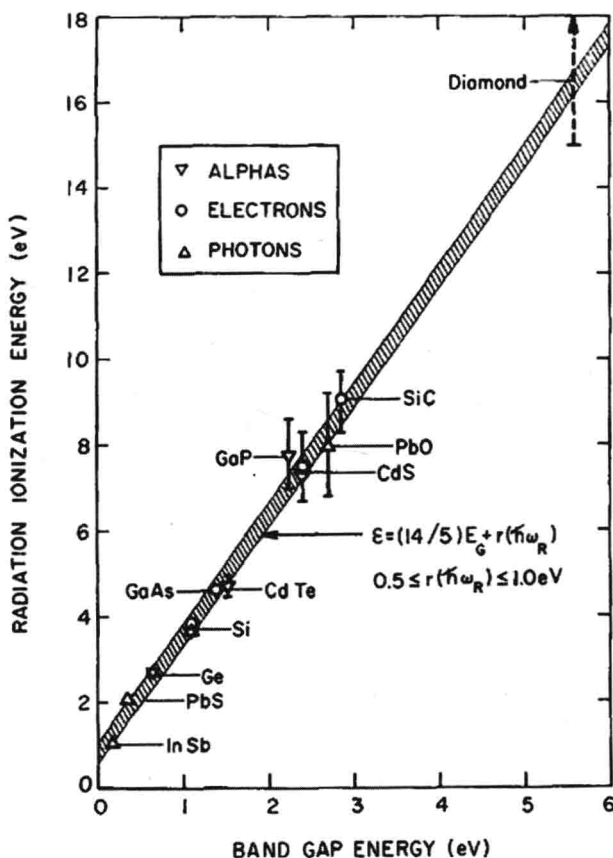


FIGURE 2. Experimental data indicating the approximate $E_{EHP} \approx 3E_{GAP}$ relation. (Reprinted with permission from Klein, 1968.) © 1968 American Institute of Physics.

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):

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

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