Ludwig Reimer

Scanning Electron Microscopy

Physics of Image Formation and Microanalysis

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With 247 Figures

Springer-Verlag
Berlin Heidelberg New York Tokyo

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ISBN 3-540-13530-8 Springer-Verlag Berlin Heidelberg New York Tokyo
ISBN 0-387-13530-8 Springer-Verlag New York Heidelberg Berlin Tokyo

Library of Congress Cataloging in Publication Data. Reimer, Ludwig, 1928–. Scanning electron microscopy. (Springer series in optical sciences ; v. 45) Bibliography: p. Includes index. 1. Scanning electron microscope. I. Title. II. Series QH212.S3R452 1985 535'.3325 85-12627

Typesetting: Daten- und Lichtsatz-Service, Würzburg
Offsetprinting and bookbinding: Graphischer Betrieb Konrad Triltsch, Würzburg
2153/3130-543210

Preface

The aim of this book is to outline the physics of image formation, electron-specimen interactions, imaging modes, the interpretation of micrographs and the use of quantitative modes in scanning electron microscopy (SEM). It forms a counterpart to *Transmission Electron Microscopy* (Vol. 36 of this Springer Series in Optical Sciences). The book evolved from lectures delivered at the University of Münster and from a German text entitled *Raster-Elektronenmikroskopie* (Springer-Verlag), published in collaboration with my colleague Gerhard Pfefferkorn.

In the introductory chapter, the principles of the SEM and of electron-specimen interactions are described, the most important imaging modes and their associated contrast are summarized, and general aspects of elemental analysis by x-ray and Auger electron emission are discussed.

The electron gun and electron optics are discussed in Chap. 2 in order to show how an electron probe of small diameter can be formed, how the electron beam can be blanked at high frequencies for time-resolving experiments and what problems have to be taken into account when focusing.

In Chap. 3, elastic and inelastic scattering is discussed in detail. Usually, the elastic scattering is described as Rutherford scattering at a screened nucleus but we show that Mott's scattering theory is more correct and that large differences can occur; this has an effect on SEM results in which elastic scattering is involved. The inelastic scattering causes deceleration of the electrons and we present the reasoning behind the Bethe continuous-slowing-down approximation in detail because it is the most important model used in diffusion models and in the discussion of specimen damage processes. In Chap. 4, the experimental findings and the theoretical models concerning backscattered and secondary electrons and x-ray and Auger electron emission are outlined.

Chapter 5 describes the detector systems employed for secondary and backscattered electrons and their signal-to-noise ratios, electron spectrometers for energy filtering, x-ray spectrometers and light collection systems for cathodoluminescence. The chapter ends with a discussion of the problems of image recording, and of analogue and digital image processing.

Chapter 6 presents the typical types of contrast that can be created with secondary and backscattered electrons and demonstrates how the physics of electron-specimen interactions can be used together with an improved detector strategy to make SEM more quantitative. In Chap. 7, the electron-

beam-induced current (EBIC) mode for semiconductors and its capacity for measuring semiconductor and device parameters are outlined. A section follows on cathodoluminescence and various other modes, of which the thermal-wave acoustic mode is likely to attract considerable interest.

The determination of crystal structure and orientation from electron channelling patterns (ECP), electron back-scattering patterns (EBSP) and x-ray Kossel patterns is described in Chap. 8, which opens with a brief review of the kinematical and dynamical theories of electron diffraction and of Bloch waves as these are essential for an understanding of these diffraction effects at solid specimens. The final chapter evaluates the correction procedures used to give quantitative information about elemental concentrations by x-ray microanalysis and discusses the problems that can arise when analysing tilted specimens, specimen coatings, particles on substrates and biological tissues. It ends with a survey of different types of x-ray imaging modes.

Electron microscopists who first use the TEM are much more conscious of the problems of image interpretation because the difference between electron and light microscopy is obvious. A SEM produces such beautiful images, which are in some respects comparable to illumination with light, that many SEM users do not give much thought to the origin of the contrast. However, when the contrast needs to be discussed in more detail and the SEM signals are to be used more quantitatively, it becomes necessary to know more about the physics of SEM. It is the aim of this book to provide this knowledge together with ample references which cannot, however, be complete.

Just as for the book about transmission electron microscopy, a special acknowledgement is due to P. W. Hawkes for revising the English text and to K. Brinkmann and Mrs. R. Dingerdissen for preparing the figures.

Münster, November 1984 *L. Reimer*

List of Abbreviations

ADC	Analogue-to-digital converter
AE	Auger electrons
AES	Auger electron spectrometry
BSE	Backscattered electrons
CL	Cathodoluminescence
CMA	Cylindrical mirror analyser
CRT	Cathode-ray tube
DAC	Digital-to-analogue converter
EBIC	Electron-beam-induced current
EBIV	Electron-beam-induced voltage
EBSP	Electron backscattering pattern
ECP	Electron channelling pattern
EDS	Energy-dispersive spectrometer (-metry) for x-ray quanta
ELS	Energy-loss spectroscopy
ESCA	Electron spectroscopy for chemical analysis
ETD	Everhart-Thornley detector
FET	Field-effect transistor
FFT	Fast Fourier transform
FWHM	Full width at half maximum
HEED	High-energy electron diffraction
LEED	Low-energy electron diffraction
LLE	Low-loss electrons
MCA	Multichannel analyser
PE	Primary electrons
PM	Photomultiplier
RHEED	Reflexion high-energy electron diffraction
rms	Root mean square value
SC	Specimen current
SE	Secondary electrons
SEM	Scanning electron microscope (microscopy)
SEMM	Scanning electron mirror microscopy
Si(Li)	Lithium-drifted silicon detector for x-rays
SIMS	Secondary ion mass spectroscopy
SNR	Signal-to-noise ratio
STEM	Scanning transmission electron microscope (microscopy)
TE	Transmitted electrons

TEM	Transmission electron microscope (microscopy)
TRIX	Total rate imaging with x-rays
TV	Television
UHV	Ultra-high vacuum
WDS	Wavelength-dispersive spectrometer (-metry) for x-ray quanta
XPS	X-ray photoelectron spectroscopy
XRMA	X-ray microanalysis
ZAF	Atomic number (Z)-Absorption-Fluorescence correction of x-ray microanalysis

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Contents

1. Introduction

1.1 Principle of the Scanning Electron Microscope

The principle of the scanning electron microscope (SEM) is shown in Fig. 1.1. Electrons from a thermionic or field-emission cathode are accelerated by a voltage of 1–50 kV between cathode and anode. The smallest beam cross-section at the gun – the crossover – with a diameter of the order of 10–50 μm for thermionic and 10–100 nm for field-emission guns, is demagnified by a two- or three-stage electron lens system, so that an electron probe of diameter 1–10 nm carrying an electron probe current of 10^{-10}–10^{-12} A is formed at the specimen surface. For modes of operation that need a higher electron-probe current of 10^{-9}–10^{-8} A, the electron-probe diameter increases to 0.1–1 μm.

The final probe-forming lens has to operate with a relatively long working distance, that is, the distance between specimen and lower pole-piece, so that the various particles and quanta emitted can be collected with the desired efficiency and if necessary, with zero magnetic field at the specimen. This requirement increases the spherical aberration of the probe-forming lens and, therefore, the smallest attainable electron-probe size. Electron-probe current, aperture and size can all be varied but not independently by changing the excitations of the first condenser lenses and the aperture-limiting diaphragm in the last probe-forming lens. Apertures of the order of ten milliradians are used for routine work and high resolution. One to two orders of magnitude smaller apertures are necessary to increase the depth of focus and to improve the angular resolution in electron channelling patterns.

A deflection coil system in front of the last lens scans the electron probe in a raster across the specimen and in synchronism with the electron beam of a separate cathode-ray tube (CRT). The intensity of the CRT is modulated by one of the signals recorded (Sect. 1.3) to form an image. The magnification can be increased simply by decreasing the scan-coil current and keeping the image size of $10 \times 10\,\text{cm}^2$ on the CRT constant. Figure 1.2 shows a series of images with increasing magnification.

Further beam-deflection modes involve rocking of the electron beam when the electron probe is at rest and the angle of incidence is raster-scanned to form electron channelling patterns for crystal analysis; periodic change of the angle of incidence for recording stereo images at TV frequencies; and periodic blanking

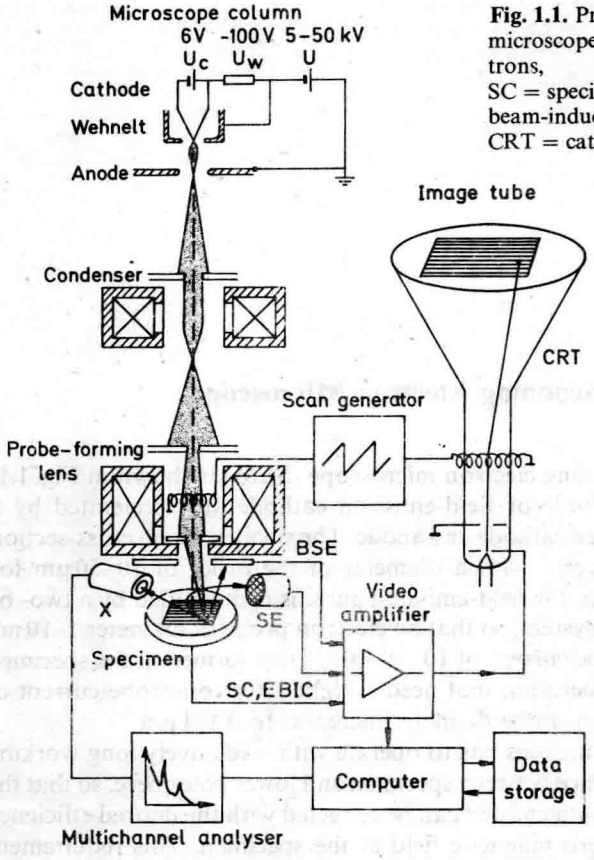

Fig. 1.1. Principle of the scanning electron microscope (BSE = backscattered electrons, SE = secondary electrons, SC = specimen current, EBIC = electron-beam-induced current, X = x-rays, CRT = cathode-ray tube)

or chopping of the electron beam up to frequencies in the GHz region for the stroboscopic modes and time-resolved signals.

The electron-probe aperture, that is, the semi-apex angle of the convergent cone of electron trajectories, is small – of the order of a few tens of milliradians – with the result that the depth of focus is much larger than in light microscopy. Specimens with large variations in depth can be sharply imaged even at the lowest magnification of 20–50 times (Fig. 1.3).

Another advantage of SEM is the wide variety of electron-specimen interactions that can be used to form an image and to furnish qualitative and quantitative information.

The large depth of focus, the excellent contrast and the straightforward preparation of solid specimens are the reasons for the considerable success and widespread use of scanning electron microscopy in the imaging of surfaces over the past decades [1.2–11]. However, we should keep in mind that the imaging of surface topography by platinum-shadowed carbon replicas in a transmission