PHY

国外物理名著系列 17

（影印版）

Fundamentals of Nanoscale Film Analysis

纳米薄膜分析基础

T.L.Alford L.C.Feldman J.W.Mayer

科学出版社
www.sciencep.com

国外物理名著系列　17

Fundamentals of Nanoscale Film Analysis

纳米薄膜分析基础

T. J. Alford, L. C. Feldman, J. W. Mayer

江苏工业学院图书馆
藏书章

科学出版社
北京

图字:01-2007-2253

T. L. Alford, L. C. Feldman, J. W. Mayer: Fundamentals of Nanoscale Film Analysis

© 2007 Springer Scince+Business Media, Inc.

This reprint has been authorized by Springer-Verlag (Berlin/Heidelberg/New York) for sale in the People's Republic of China only and not for export therefrom.

本书英文影印版由德国施普林格出版公司授权出版。未经出版者书面许可，不得以任何方式复制或抄袭本书的任何部分。本书仅限在中华人民共和国销售，不得出口。版权所有，翻印必究。

图书在版编目(CIP)数据

纳米薄膜分析基础＝Fundamentals of Nanoscale Film Analysis：英文/(美)阿尔弗德(Alford, T. L.)等编著. —影印本. —北京：科学出版社，2008
(国外物理名著系列；17)
ISBN 978-7-03-022259-6
Ⅰ. 纳… Ⅱ. 阿… Ⅲ. 纳米材料-薄膜-英文 Ⅳ. TB383
中国版本图书馆 CIP 数据核字(2008)第 082913 号

责任编辑：王飞龙 胡凯 鄢德平/责任印制：赵德静/封面设计：陈敬

科学出版社 出版
北京东黄城根北街 16 号
邮政编码：100717
http://www.sciencep.com
双青印刷厂 印刷
科学出版社发行 各地新华书店经销
*
2008 年 6 月第 一 版 开本：B5(720×1000)
2008 年 6 月第一次印刷 印张：22 1/4
印数：1～3 000 字数：731 000

定价：68.00 元
(如有印装质量问题，我社负责调换〈双青〉)

国外物理名著系列序言

对于国内的物理学工作者和青年学生来讲，研读国外优秀的物理学著作是系统掌握物理学知识的一个重要手段。但是，在国内并不能及时、方便地买到国外的图书，且国外图书不菲的价格往往令国内的读者却步，因此，把国外的优秀物理原著引进到国内，让国内的读者能够方便地以较低的价格购买是一项意义深远的工作，将有助于国内物理学工作者和青年学生掌握国际物理学的前沿知识，进而推动我国物理学科研和教学的发展。

为了满足国内读者对国外优秀物理学著作的需求，科学出版社启动了引进国外优秀著作的工作，出版社的这一举措得到了国内物理学界的积极响应和支持，很快成立了专家委员会，开展了选题的推荐和筛选工作，在出版社初选的书单基础上确定了第一批引进的项目，这些图书几乎涉及了近代物理学的所有领域，既有阐述学科基本理论的经典名著，也有反映某一学科专题前沿的专著。在选择图书时，专家委员会遵循了以下原则：基础理论方面的图书强调“经典”，选择了那些经得起时间检验、对物理学的发展产生重要影响、现在还不“过时”的著作（如：狄拉克的《量子力学原理》）。反映物理学某一领域进展的著作强调“前沿”和“热点”，根据国内物理学研究发展的实际情况，选择了能够体现相关学科最新进展，对有关方向的科研人员和研究生有重要参考价值的图书。这些图书都是最新版的，多数图书都是2000年以后出版的，还有相当一部分是2006年出版的新书。因此，这套丛书具有权威性、前瞻性和应用性强的特点。由于国外出版社的要求，科学出版社对部分图书进行了少量的翻译和注释（主要是目录标题和练习题），但这并不会影响图书“原汁原味”的感觉，可能还会方便国内读者的阅读和理解。

“他山之石，可以攻玉”，希望这套丛书的出版能够为国内物理学工作者和青年学生的工作和学习提供参考，也希望国内更多专家参与到这一工作中来，推荐更多的好书。

杨国桢

中国科学院院士

中国物理学会理事长

To our wives and children,
Katherine and Dylan,
Betty, Greg, and Dana,
and
Betty, Jim, John, Frank, Helen, and Bill

此为试读,需要完整PDF请访问: www.ertongbook.com

Preface

A major feature in the evolution of modern technologies is the important role of surfaces and near surfaces on the properties of materials. This is especially true at the nanometer scale. In this book, we focus on the fundamental physics underlying the techniques used to analyze surfaces and near surfaces. New analytical techniques are emerging to meet the technological requirements, and all are based on a few processes that govern the interactions of particles and radiation with matter. Ion implantation and pulsed electron beams and lasers are used to modify composition and structure. Thin films are deposited from a variety of sources. Epitaxial layers are grown from molecular beams and physical and chemical vapor techniques. Oxidation and catalytic reactions are studied under controlled conditions. The key to these methods has been the widespread availability of analytical techniques that are sensitive to the composition and structure of solids on the nanometer scale.

This book focuses on the physics underlying the techniques used to analyze the surface region of materials. This book also addresses the fundamentals of these processes. From an understanding of processes that determine the energies and intensities of the emitted energetic particles and/or photons, the application to materials analysis follows directly.

Modern materials analysis techniques are based on the interaction of solids with interrogating beams of energetic particles or electromagnetic radiation. These interactions and their resulting radiation/particles are based upon on fundamental physics. Detection of emergent radiation and energetic particles provides information about the solid's composition and structure. Identification of elements is based on the energy of the emergent radiation/particle; atomic concentration is based on the intensity of the emergent radiation. We discuss in detail the relevant analytical techniques used to uncover this information. Coulomb scattering from atoms (Rutherford backscattering spectrometry), the formation of inner shell vacancies in the electronic structure (X-ray photoelectron spectroscopy), transitions between levels (electron microprobe and Auger electron spectroscopies), and coherent scattering (X-ray and electron diffractometry) are fundamental to materials analysis. Composition depth profiles are obtained with heavy-ion sputtering in combination with surface-sensitive techniques (electron spectroscopies and secondary ion mass spectrometry). Depth profiles are also found from energy loss of light ions (Rutherford backscattering and prompt nuclear analyses). Structures of surface layers are characterized using diffraction (X-ray, electron, and low-energy electron diffraction), elastic scattering (ion channeling), and scanning probes (tunneling and atomic force microscopies).

Because this book focuses on the fundamentals of modern surface analysis at the nanometer scale, we have provided derivations of the basic parameters—energy and cross section or transition probability. The book is organized so that we start with the classical concepts of atomic collisions as applied to Rutherford scattering (Chapter 2), energy loss (Chapter 3), sputtering (Chapter 4), channeling (Chapter 5), and electron interactions (Chapter 6). An overview is given of diffraction techniques in both real space (X-ray diffraction, Chapter 7) and reciprocal space (electron diffraction, Chapter 8) for structural analysis. Wave mechanics is required for an understanding of photoelectric cross sections and fluorescence yields; we review the wave equation and perturbation theory in Chapter 9. We use these relations to discuss photoelectron spectroscopy (Chapter 10), radiative transitions (Chapter 11), and nonradiative transitions (Chapter 12). Chapter 13 discusses the application of nuclear techniques to thin film analysis. Finally, Chapter 14 presents a discussion of scanning probe microscopy.

The current volume is a significant expansion of the previous work, *Fundamentals of Thin Films Analysis*, by Feldman and Mayer. New chapters have been added reflecting the progress that has been made in analysis of ultra thin films and nanoscale structures.

All the authors have been engaged heavily in research programs centered on materials analysis; we realize the need for a comprehensive treatment of the analytical techniques used in nanoscale surface and thin film analysis. We find that a basic understanding of the processes is important in a field that is rapidly changing. Instruments may change, but the fundamental processes will remain the same.

This book is written for materials scientists and engineers interested in the use of spectroscopies and/or spectometries for sample characterization; for materials analysts who need information on techniques that are available outside their laboratory; and particularly for seniors and graduate students who will use this new generation of analytical techniques in their research.

We have used the material in this book in senior/graduate-level courses at Cornell University, Vanderbilt University, and Arizona State University, as well as in short courses for scientists and engineers in industry around the world. We wish to thank Dr. N. David Theodore for his review of Chapters 7 and 8. We also thank Timothy Pennycook for proofreading the manuscript. We thank Jane Jorgensen and Ali Avcisoy for their drawings and artwork.

Contents

Preface xi

1. An Overview: Concepts, Units, and the Bohr Atom 1
   - 1.1 Introduction 1
   - 1.2 Nomenclature 2
   - 1.3 Energies, Units, and Particles 6
   - 1.4 Particle–Wave Duality and Lattice Spacing 8
   - 1.5 The Bohr Model 9
   - Problems 10

2. Atomic Collisions and Backscattering Spectrometry 12
   - 2.1 Introduction 12
   - 2.2 Kinematics of Elastic Collisions 13
   - 2.3 Rutherford Backscattering Spectrometry 16
   - 2.4 Scattering Cross Section and Impact Parameter 17
   - 2.5 Central Force Scattering 18
   - 2.6 Scattering Cross Section: Two-Body 21
   - 2.7 Deviations from Rutherford Scattering at Low and High Energy 23
   - 2.8 Low-Energy Ion Scattering 24
   - 2.9 Forward Recoil Spectrometry 28
   - 2.10 Center of Mass to Laboratory Transformation 28
   - Problems 31

3. Energy Loss of Light Ions and Backscattering Depth Profiles 34
   - 3.1 Introduction 34
   - 3.2 General Picture of Energy Loss and Units of Energy Loss 34
   - 3.3 Energy Loss of MeV Light Ions in Solids 35
   - 3.4 Energy Loss in Compounds—Bragg's Rule 40
   - 3.5 The Energy Width in Backscattering 40
   - 3.6 The Shape of the Backscattering Spectrum 43
   - 3.7 Depth Profiles with Rutherford Scattering 45
   - 3.8 Depth Resolution and Energy-Loss Straggling 47

3.9 Hydrogen and Deuterium Depth Profiles 50
3.10 Ranges of H and He Ions 52
3.11 Sputtering and Limits to Sensitivity 54
3.12 Summary of Scattering Relations 55
Problems 55

4. Sputter Depth Profiles and Secondary Ion Mass Spectroscopy 59
4.1 Introduction 59
4.2 Sputtering by Ion Bombardment—General Concepts 60
4.3 Nuclear Energy Loss 63
4.4 Sputtering Yield 67
4.5 Secondary Ion Mass Spectroscopy (SIMS) 69
4.6 Secondary Neutral Mass Spectroscopy (SNMS) 73
4.7 Preferential Sputtering and Depth Profiles 75
4.8 Interface Broadening and Ion Mixing 77
4.9 Thomas–Fermi Statistical Model of the Atom 80
Problems 81

5. Ion Channeling 84
5.1 Introduction 84
5.2 Channeling in Single Crystals 84
5.3 Lattice Location of Impurities in Crystals 88
5.4 Channeling Flux Distributions 89
5.5 Surface Interaction via a Two-Atom Model 92
5.6 The Surface Peak 95
5.7 Substrate Shadowing: Epitaxial Au on Ag(111) 97
5.8 Epitaxial Growth 99
5.9 Thin Film Analysis 101
Problems 103

6. Electron–Electron Interactions and the Depth Sensitivity of Electron Spectroscopies 105
6.1 Introduction 105
6.2 Electron Spectroscopies: Energy Analysis 105
6.3 Escape Depth and Detected Volume 106
6.4 Inelastic Electron–Electron Collisions 109
6.5 Electron Impact Ionization Cross Section 110
6.6 Plasmons 111
6.7 The Electron Mean Free Path 113
6.8 Influence of Thin Film Morphology on Electron Attenuation 114
6.9 Range of Electrons in Solids 118
6.10 Electron Energy Loss Spectroscopy (EELS) 120
6.11 Bremsstrahlung 124
Problems 126

7. X-ray Diffraction 129
7.1 Introduction 129
7.2 Bragg's Law in Real Space 130
7.3 Coefficient of Thermal Expansion Measurements 133
7.4 Texture Measurements in Polycrystalline Thin Films 135
7.5 Strain Measurements in Epitaxial Layers 137
7.6 Crystalline Structure 141
7.7 Allowed Reflections and Relative Intensities 143
Problems 149

8. Electron Diffraction 152
8.1 Introduction 152
8.2 Reciprocal Space 153
8.3 Laue Equations 157
8.4 Bragg's Law 158
8.5 Ewald Sphere Synthesis 159
8.6 The Electron Microscope 160
8.7 Indexing Diffraction Patterns 166
Problems 172

9. Photon Absorption in Solids and EXAFS 174
9.1 Introduction 174
9.2 The Schrödinger Equation 174
9.3 Wave Functions 176
9.4 Quantum Numbers, Electron Configuration, and Notation 179
9.5 Transition Probability 180
9.6 Photoelectric Effect—Square-Well Approximation 181
9.7 Photoelectric Transition Probability for a Hydrogenic Atom 184
9.8 X-ray Absorption 185
9.9 Extended X-ray Absorption Fine Structure (EXAFS) 189
9.10 Time-Dependent Perturbation Theory 192
Problems 197

10. X-ray Photoelectron Spectroscopy 199
10.1 Introduction 199
10.2 Experimental Considerations 199
10.3 Kinetic Energy of Photoelectrons 203
10.4 Photoelectron Energy Spectrum 204
10.5 Binding Energy and Final-State Effects 206
10.6 Binding Energy Shifts—Chemical Shifts 208
10.7 Quantitative Analysis 210
Problems 211

11. Radiative Transitions and the Electron Microprobe 214
- 11.1 Introduction 214
- 11.2 Nomenclature in X-Ray Spectroscopy 215
- 11.3 Dipole Selection Rules 215
- 11.4 Electron Microprobe 216
- 11.5 Transition Rate for Spontaneous Emission 220
- 11.6 Transition Rate for K_α Emission in Ni 220
- 11.7 Electron Microprobe: Quantitative Analysis 222
- 11.8 Particle-Induced X-Ray Emission (PIXE) 226
- 11.9 Evaluation of the Transition Probability for Radiative Transitions ... 227
- 11.10 Calculation of the K_β/K_α Ratio 230
- Problems 231

12. Nonradiative Transitions and Auger Electron Spectroscopy 234
- 12.1 Introduction 234
- 12.2 Auger Transitions 234
- 12.3 Yield of Auger Electrons and Fluorescence Yield 241
- 12.4 Atomic Level Width and Lifetimes 243
- 12.5 Auger Electron Spectroscopy 244
- 12.6 Quantitative Analysis 248
- 12.7 Auger Depth Profiles 249
- Problems 252

13. Nuclear Techniques: Activation Analysis and Prompt Radiation Analysis .. 255
- 13.1 Introduction 255
- 13.2 Q Values and Kinetic Energies 259
- 13.3 Radioactive Decay 262
- 13.4 Radioactive Decay Law 265
- 13.5 Radionuclide Production 266
- 13.6 Activation Analysis 266
- 13.7 Prompt Radiation Analysis 267
- Problems 274

14. Scanning Probe Microscopy 277
- 14.1 Introduction 277
- 14.2 Scanning Tunneling Microscopy 279
- 14.3 Atomic Force Microscopy 284

Appendix 1. K_M for $^4He^+$ as Projectile and Integer Target Mass 291
Appendix 2. Rutherford Scattering Cross Section of the Elements for 1 MeV $^4He^+$ 294
Appendix 3. $^4He^+$ Stopping Cross Sections 296
Appendix 4. Electron Configurations and Ionization Potentials of Atoms 299
Appendix 5. Atomic Scattering Factors 302
Appendix 6. Electron Binding Energies 305

此为试读，需要完整PDF请访问：www.ertongbook.com

Appendix 7. X-Ray Wavelengths (nm) 309
Appendix 8. Mass Absorption Coefficient and Densities 312
Appendix 9. *KLL* Auger Energies (eV) 316
Appendix 10. Table of the Elements 319
Appendix 11. Table of Fluoresence Yields for *K*, *L*, and *M* Shells 325
Appendix 12. Physical Constants, Conversions, and Useful Combinations 327
Appendix 13. Acronyms 328

Index 330

1

An Overview: Concepts, Units, and the Bohr Atom

1.1 Introduction

Our understanding of the structure of atoms and atomic nuclei is based on scattering experiments. Such experiments determine the interaction of a beam of elementary particles—photons, electrons, neutrons, ions, etc.—with the atom or nucleus of a known element. (In this context, we consider all incident radiation as *particles*, including photons.) The classical example is Rutherford scattering, in which the scattering of incident alpha particles from a thin solid foil confirmed the picture of an atom as composed of a small positively charged nucleus surrounded by electrons in circular orbits. As these fundamental interactions became understood, the scientific community recognized the importance of the inverse process—namely, measuring the interaction of radiation with targets of unknown elements to determine atomic composition. Such determinations are called *materials analysis*. For example, alpha particles scatter from different nuclei in a distinct and well-understood manner. Measurements of the intensity and energy of the scattered particles provides a direct measure of elemental composition. The emphasis in this book is twofold: (1) to describe in a quantitative fashion those fundamental interactions that are used in modern materials analysis and (2) to illustrate the use of this understanding in practical materials analysis problems.

The emphasis in modern materials analysis is generally directed toward the structure and composition of the surface and outer few tens to hundred nanometers of the materials. The emphasis comes from the realization that the surface and near-surface regions control many of the mechanical and chemical properties of solids: corrosion, friction, wear, adhesion, and fracture. In addition, one can tailor the composition and structure of the outer layers by directed energy processes utilizing lasers or electron and ion beams, as well as by more conventional techniques such as oxidation and diffusion.

In modern materials analysis, one is concerned with the source beam (also referred to as the *incident beam* or the *probe beam* or *primary beam*) of radiation; the beam of particles—photons, electrons, neutrons, or ions; the interaction cross section; the emergent radiation; and the detection system. The primary interest of this book is the interaction of the beam with the material to be analyzed, with emphasis on the energies and intensities of emitted radiation. As we will show, the energy of the emitted particles provides the signature or identification of the atom, and the intensity tells the amount of atoms (i.e., sample composition). The radiation source and the detection system are important topics in their own right; however, the main emphasis in this book is on the ability to conduct quantitative materials analysis that depends upon interactions within the target.

1.2 Nomenclature

Materials characterization involves the quantification of the structure, composition, amount, and depth distribution of matter with the use of energetic particles (e.g., ions, neutrons, alpha particles, protons, and electrons) and energetic photons (e.g., infrared radiation, visible light, UV light, X-rays, and gamma rays). Any materials-characterization techniques can be described in the following manner. The incident *probe beam* of energetic photons or particles *interrogates* the solid. The incident particle or photon reacts with the solid in various manners; these reactions (R_x) induce the emission of a variety of detected beams in the form of energetic particles or photons, i.e., the detected beam (Fig. 1.1). Hence, the primary interest of this book is in using the reaction (between the beam and the solid) and the intensity and energy of the detected beam to analyze solids. Since the energy of the detected particle/photon is measured, the actual names of the various techniques have the prefix SPECTRO, meaning *energy measurement*. The suffix gives information about the relationship between the specific incidence *photon/particle* and the detected *photon/particle*. For example, if the incident species is the same as the emitted species, the technique is a SPECTROMETRY: Rutherford backscattering spectrometry and X-ray diffractometry. If the incident species is different from the emitted species, then the term SPECTROSCOPY is used: Auger electron spectroscopy and X-ray photoelectron spectroscopy.

There is an impressive array of experimental techniques available for the analysis of solids. Figure 1.2 gives the flavor of the possible combinations. In some cases, the same incident and emergent radiation is employed (we will use the general terms *radiation* and *particles* for photons, electrons, ions, etc.). Listed below are examples, with commonly used acronyms in parentheses.

Primary electron in, Auger electron out: Auger electron spectroscopy (AES)
Alpha particle in, alpha particle out: Rutherford backscattering spectrometry (RBS)
Primary X-ray in, characteristic X-ray out: X-ray fluorescence spectroscopy (XRF)

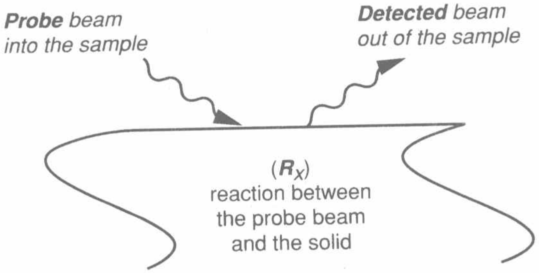


FIGURE 1.1. Schematic of the fundamentals of materials characterization. The probe beam of energetic photons or particles interrogates the solid. The incident particle or photon reacts (R_x) and induces the emission of a variety of detected beams in the form of energetic particles or photons, i.e., the detected beam.

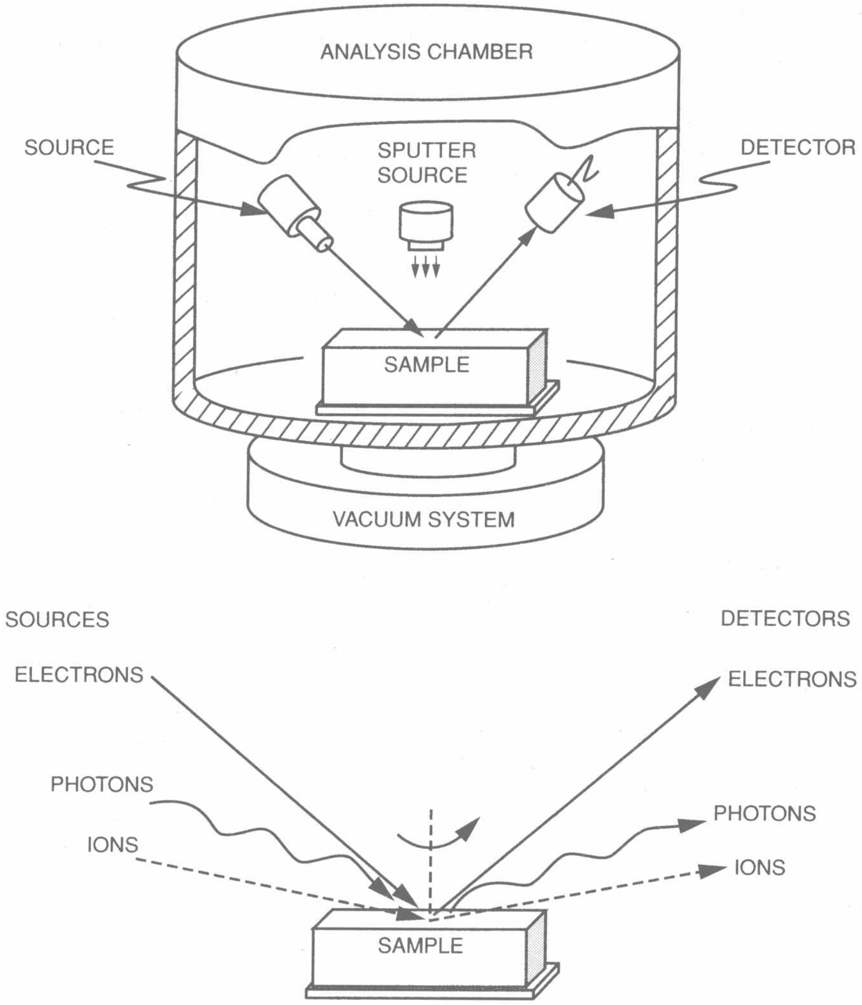

ANALYSIS CHAMBER
SOURCE
SPUTTER SOURCE
DETECTOR
SAMPLE
VACUUM SYSTEM
SOURCES
DETECTORS
ELECTRONS
ELECTRONS
PHOTONS
PHOTONS
IONS
IONS
SAMPLE

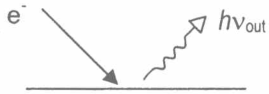
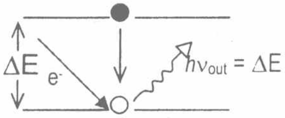
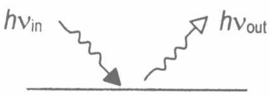
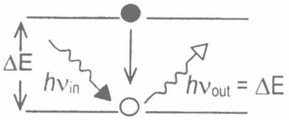
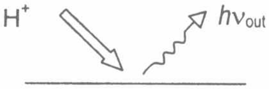
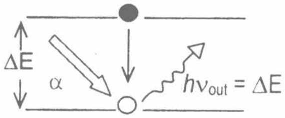
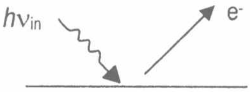
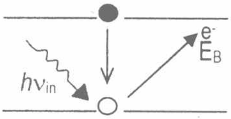
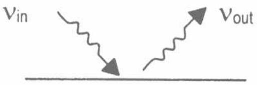
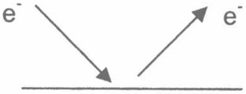
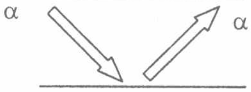
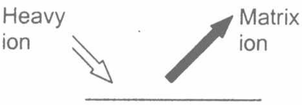
FIGURE 1.2. Schematic of radiation sources and detectors in thin film analysis techniques. Analytical probes are represented by almost any combination of source and detected radiation, i.e., photons in and photons out or ions in and photon out. Many chambers will also contain sample erosion facilities such as an ion sputtering as well as an evaporation apparatus for deposition of materials onto a clean substrate under vacuum.

In other cases, the incident and emergent radiation differ as indicated below:

X-ray in, electron out: X-ray photoelectron spectroscopy (XPS)
Electron in, X-ray out: electron microprobe analysis (EMA)
Ion in, target ion out: secondary ion mass spectroscopy (SIMS)

A beam of particles incident on a target either scatters elastically or causes an electronic transition in an atom. The scattered particle or the energy of the emergent radiation contains the signature of the atom. The energy levels in the transition are

TABLE 1.1. Nomenclature of many techniques available for the analysis of materials. The name of a given technique often provides a complete or partial description of the technique.

Method	In	Out	R_x
Energy Dispersive X-rays (EDX) Spectroscopy	 e^-	$h\nu_{out}$	 ΔE e^- $h\nu_{out} = \Delta E$
X-ray Fluorescence (XRF) Spectroscopy	 $h\nu_{in}$	$h\nu_{out}$	 ΔE $h\nu_{in}$ $h\nu_{out} = \Delta E$
Particle Induced X-ray Emission (PIXE) Spectroscopy	 H^+	$h\nu_{out}$	 ΔE α $h\nu_{out} = \Delta E$
X-ray Photoelectron Spectroscopy (XPS)	 $h\nu_{in}$	e^-	 $h\nu_{in}$ e^- E_B
X-ray Diffractometry (XRD)	 ν_{in}	ν_{out}	Coherent Scattering $\nu_{in} = \nu_{out}$ (particle characteristics)
Electron Diffractometry (ED)	 e^-	e^-	Coherent Scattering $\nu_{in} = \nu_{out}$ (wave characteristic)
Rutherford Backscattering Spectrometry (RBS)	 α	α	Elastic Scattering
Secondary Ion Mass Spectroscopy (SIMS)	 Heavy ion	Matrix ion	Sputtered Ion (erosion due to momentum transfer)

characteristic of a given atom; hence, measurement of the energy spectrum of the emergent radiation allows identification of the atom. Table 1.1 gives a summary of various techniques based on the nomenclature of the incident *probe beam*, the induced emission, and the detected beam.

The number of atoms per cm^2 in a target is found from the relation between the number, I, of incident particles and the number of interactions. The term *cross section* is used as a quantitative measure of an interaction between an incident

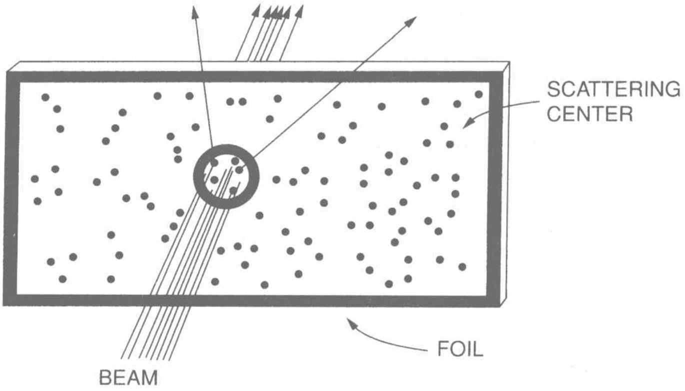


FIGURE 1.3. Illustration of the concept of cross section and scattering. The central circle defines a unit area of a foil containing a random array of scattering centers. In this example, there are five scattering centers per unit area. Each scattering center has an area (the cross section for scattering) of 1/20 unit area; therefore, the probability of scattering is 5/20, or 0.25. Then a fraction (0.25 in this example) of the incident beam will be scattered, i.e., 2 out of 8 trajectories in the drawing. A measure of the fraction of the scattered beam is a measure of the probability ($P = Nt\sigma$, Eq. 1.1). If the foil thickness and density are known, Nt can be calculated, yielding a direct measure of the cross section.

particle and an atom. The cross section σ for a given process is defined through the probability, P:

$$P = \frac{\text{Number of interactions}}{\text{Number of incident particles}}. \tag{1.1}$$

For a target containing Nt atoms per unit area perpendicular to an incident beam of I particles, the number of interactions is $I\sigma Nt$. From knowledge of detection efficiency for measuring the emergent radiation containing the signature of the transition, the number of atoms and ultimately the target composition can be found (Fig. 1.3).

The information required from analytical techniques is the species identification, concentration, depth distribution, and structure. The available analytical techniques have different capabilities to meet these requirements. The choice of analysis method depends upon the nature of the problem. For example, chemical bonding information can be obtained from techniques that rely upon transitions in the electronic structure around the atoms—the electron spectroscopies. Structural determination is found from diffraction or particle channeling techniques.

In the following chapters, we are mostly concerned with materials analysis in the outer microns of the sample's surface and near-surface region. We emphasize the energy of the emergent radiation as an identification of the element and the intensity of the radiation as a measure of the amount of material. These are the basic principles that provide the foundation for the different analytical techniques.

此为试读，需要完整PDF请访问：www.ertongbook.com