

Subash Mahajan • K.S. Sree Harsha

PRINCIPLES OF GROWTH AND PROCESSING OF SEMICONDUCTORS



McGraw-Hill Series in Materials Science and Engineering

Principles of Growth and Processing of Semiconductors

S. Mahajan

Arizona State University

K. S. Sree Harsha

San Jose State University



Boston Burr Ridge, IL Dubuque, IA Madison, WI New York San Francisco St. Louis
Bangkok Bogotá Caracas Lisbon London Madrid Mexico City Milan
New Delhi Seoul Singapore Sydney Taipei Toronto

WCB/McGraw-Hill

A Division of The McGraw-Hill Companies

PRINCIPLES OF GROWTH AND PROCESSING OF SEMICONDUCTORS

Copyright © 1999 by The McGraw-Hill Companies, Inc. All rights reserved. Printed in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written permission of the publisher.

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 0 DOC/DOC 9 0 9 8 7

ISBN 0-07-039605-1

Vice president and editorial director: *Kevin T. Kane*

Publisher: *Tom Casson*

Senior administrative assistant: *Jean Turrise*

Marketing manager: *John T. Wannemacher*

Senior project manager: *Denise Santor-Mitzit*

Production supervisor: *Michael R. McCormick*

Designer: *Jennifer Hollingsworth*

Compositor: *Interactive Composition Corporation*

Typeface: 10/12 Linotype/Adobe Times Roman

Printer: *R. R. Donnelley & Sons Company*

Library of Congress Cataloging-in-Publication Data

Mahajan, Subhash.

Principles of growth and processing of semiconductors / S.

Mahajan, K.S. Sree Harsha.

p. cm.

Includes index.

ISBN 0-07-039605-1

I. Semiconductors—Design and construction. I. SreeHarsha, K. S.

II. Title.

TK7871.85.M295 1998

621.3815'2—dc21

98-3385

CIP

To our families and parents

PREFACE

Fabricating state-of-the-art integrated circuits is a joint endeavor between chemists, chemical engineers, electrical engineers, materials scientists, and physicists. Each group's expertise is not broad enough to appreciate all the interdisciplinary issues in the microelectronics industry. For example, electrical engineers and physicists, though familiar with semiconducting materials and devices, are not exposed to defects in solids or crystal growth. This book builds bridges across various disciplines. We begin with the physics of semiconductors and devices, and follow with the growth and processing of semiconductors. We emphasize how defects arise during growth and processing and what effects these defects have on the device behavior. This approach will help prepare students for the eclectic microelectronics industry.

In planning this book, we asked ourselves the following question: What is a suitable background for a student intending to join the microelectronics industry? It became apparent that chemists, chemical engineers, and materials scientists need exposure to the physics of semiconductors and principles of semiconducting devices, so we decided to discuss these topics in Chapters 1 and 2. Even though materials scientists are familiar with defects in solids, they do not learn specific characteristics of defects in semiconductors. We cover these characteristics in Chapter 3, which also includes the necessary background on various types of defects for students from other disciplines. Since real materials contain defects and since semiconducting behavior is affected by impurities, evaluation of semiconductors is essential. Therefore, we cover structural, chemical, and electrical evaluations of semiconductors in Chapter 4. To illustrate the salient features of each technique and its limitations, we have included one or two examples in each case. Furthermore, semiconducting devices require doped single crystals because grain boundaries act as carrier recombination centers. We cover crystal growth in Chapter 5. In particular, we emphasize the reduction of dislocation densities in as-grown crystals, the precipitation of oxygen in Czochralski silicon, and the formation of impurity striations. For efficient operation, most devices require epitaxial growth, a topic we cover in Chapter 6, along with the introduction of defects during epitaxy and heteroepitaxy.

To convert the crystal into a device requires several fabrication steps. These steps include oxidation, diffusion, ion implantation, metallization, lithography, and etching. The growth of a thermal oxide on silicon forms the backbone of ULSI technology. We cover oxide growth kinetics, thermodynamics, structure and oxidation-induced stacking faults in Chapter 7. The fabrication of several devices requires a local change in carrier concentration and conductivity type using diffusion and ion implantation. We cover these processes in Chapters 8 and 9. External and inter-device communication requires metal contacts and interconnects. We consider the techniques available for depositing contacts and interconnects and other relevant issues in Chapter 10. Circuit fabrication requires transferring a circuit pattern on a

wafer using lithography and etching. We discuss the principles of these two technologies and their limitations in Chapter 11. In Chapter 12, we cover some of the future challenges in growth and processing of semiconductors.

To flesh out the concepts being developed, we have provided problems and their solutions within each chapter, as well as problem material at the end of each chapter. Furthermore, the approach underlying this book has been tested at Carnegie Mellon University and San Jose University, and the student response has been very encouraging.

The authors are grateful to Professor D. W. Greve, Professor M. E. McHenry, and Professor H. Temkin for their feedback on some of the chapters. To assess the student's reaction, some of the chapters were critiqued by Sanjoy, Sunit, and Ashish Mahajan, and their contribution is much appreciated. The authors are also very much obliged to Mrs. Valerie Thompson for her impressive word processing effort and to Mr. Kelly Young for his meticulous illustrations. Finally, they are very grateful to their families for their support and patience through this arduous endeavor.

S. Mahajan
K. S. Sree Harsha

ABOUT THE AUTHORS

Subhash Mahajan received a B.Sc. degree in physical sciences from Panjab University, Chandigarh, a B.E. in metallurgy from the Indian Institute of Science, Bangalore, and a Ph.D. from the University of California, Berkeley, in materials science and engineering. He has worked at the University of Denver, the Atomic Energy Research Establishment, Harwell, England; AT&T Bell Laboratories, Murray Hill; and Carnegie Mellon University, Pittsburgh. He is currently a Professor of Electronic Materials in the Department of Chemical, Bio and Materials Engineering, Arizona State University, Tempe, Arizona.

Dr. Mahajan has lectured and published extensively on origins of defects in semiconductors and their influence on device behavior and deformation behavior of solids. He has received several honors, such as the John Bardeen Award of the Minerals, Metals and Materials Society (TMS) (and the Albert Sauveur Achievement Award of the American Society at Metals (ASM) International. In addition, Dr. Mahajan consults nationally and internationally and is a member of several leading materials societies.

K. S. Sree Harsha is a Professor of Materials Engineering in the Department of Materials Engineering of San Jose State University at San Jose, California. He received a B.Sc. degree from the University of Mysore (and also received undergraduate education in metallurgy from the Indian Institute of Science), an M.S. degree from the University of Notre Dame, and a Ph.D. from Pennsylvania State University. Dr. Sree Harsha has been teaching at San Jose State University since 1968, and has served as the chair person of the Department of Materials Engineering for twenty-one years. He has taught extensively in the areas of materials analysis, thermodynamics, semiconductor processing, and fracture mechanics. His research work includes publications in all these areas of his interest. He is a member of the Metals, Minerals Society (TMS), the Materials Research Society, and the American Society for Materials (ASM Int), and has served on several committees. He has spent several summers in industrial research, and two one-year sabbaticals at Bell Laboratories.

CONTENTS

Preface	vii
About the Authors	xi
1 Semiconductors: An Introduction	1
1.1 Behavior of Free Electrons	1
<i>1.1.1 Particle-Wave Duality / 1.1.2 Uncertainty Principle /</i>	
<i>1.1.3 Quantum Mechanical Treatment / 1.1.3.1 Energy</i>	
continuum of free electrons	
1.2 Electrons in Potential Wells	6
<i>1.2.1 Infinite Potential Well / 1.2.2 Finite-Potential Barrier</i>	
1.3 Origin of Band Gaps in a Crystal	11
<i>1.3.1 Electron in a Periodic Potential of a Crystal (Kronig-</i>	
<i>Penney Model) / 1.3.2 Perturbed Free-Electron Model /</i>	
<i>1.3.3 Velocity of an Electron in an Energy Band /</i>	
<i>1.3.4 Effective Mass of an Electron in an Energy Band /</i>	
<i>1.3.5 Holes in Solids</i>	
1.4 Electrons in Solids	19
<i>1.4.1 Fermi Energy and Fermi Distribution Function /</i>	
<i>1.4.2 Density of States in a Band / 1.4.3 Differences Between</i>	
<i>Metals, Insulators, and Semiconductors</i>	
1.5 Semiconductors	23
<i>1.5.1 Direct and Indirect Semiconductors /</i>	
<i>1.5.2 Charge Carriers in Semiconductors / 1.5.2.1 Electrons</i>	
and holes / 1.5.2.2 Intrinsic semiconductors / 1.5.2.3 Extrinsic	
semiconductors / 1.5.3 Carrier Concentrations /	
1.5.3.1 Influence of Doping on the Fermi level /	
1.5.3.2 Concentrations of electrons and holes at equilibrium /	
1.5.3.3 Temperature dependence of carrier concentrations in	
doped semiconductors / 1.5.3.4 Compensation and space-charge	
neutrality / 1.5.4 Excess Carriers in Semiconductors /	
1.5.5 Carrier Drift in Electric and Magnetic Fields	
1.6 Highlights of the Chapter	38
References	39
Further Reading	39
Problems	39

2	Principles of Semiconducting Devices	42
2.1	p–n and Metal-Semiconductor Junctions	42
2.1.1	<i>p-n Junctions</i> / 2.1.1.1 Conceptual development /	
2.1.1.2	Quantitative treatment of I–V characteristics /	
2.1.2	<i>Metal-Semiconductor Junctions</i> / 2.1.2.1 Rectifying junctions (Schottky barrier diodes) / 2.1.2.2 Nonrectifying junctions (ohmic contacts)	
2.2	Basics of Select Devices	61
2.2.1	<i>Solar Cells</i> / 2.2.2 <i>Light-Emitting Diodes</i> / 2.2.3 <i>Bipolar Junction Transistors</i> / 2.2.4 <i>Field-Effect Transistors</i> /	
2.2.4.1	Junction field-effect transistors (JFETs) / 2.2.4.2 Metal-semiconductor field-effect transistors (MESFET) /	
2.2.4.3	Metal-insulator-semiconductor field-effect transistors (MISFET)	
2.3	Highlights of the Chapter	75
	Reference	76
	Further Reading	76
	Problems	76
3	Defects	79
3.1	Crystal Structure of Important Semiconductors	79
3.2	Stacking Arrangement of {111} Planes in Diamond-Cubic and Zinc-Blende Structures	82
3.3	Structural Characteristics of Defects	83
3.3.1	<i>Zero-Dimensional Defects</i> / 3.3.2 <i>One-Dimensional Defects</i> / 3.3.3 <i>Two-Dimensional Defects</i> / 3.3.4 <i>Three-Dimensional Defects</i>	
3.4	Electronic Properties of Defects	113
3.4.1	<i>Zero-Dimensional Defects</i> / 3.4.2 <i>One-Dimensional Defects</i> / 3.4.3 <i>Two-Dimensional Defects</i> / 3.4.4 <i>Three-Dimensional Defects</i>	
3.5	Highlights of the Chapter	118
	References	118
	Problems	119
4	Evaluation of Semiconductors	122
4.1	Structural Evaluation	122
4.1.1	<i>Defect Etching</i> / 4.1.2 <i>X-Ray Topography</i> / 4.1.3 <i>Double-Crystal Diffractometry</i> / 4.1.4 <i>Transmission Electron Microscopy (TEM)</i>	

4.2	Chemical Evaluation	138
	<i>4.2.1 Neutron Activation Analysis (NAA) / 4.2.2 Electron Microprobe Analysis (EMPA) / 4.2.3 Auger Electron Spectroscopy (AES) / 4.2.4 Secondary Ion Mass Spectrometry (SIMS) / 4.2.5 Rutherford Backscattering (RBS)</i>	
4.3	Electrical and Optical Evaluations	148
	<i>4.3.1 Mobility and Carrier Concentration / 4.3.2 Minority-Carrier Lifetime / 4.3.3 Deep-Level Transient Spectroscopy (DLTS) / 4.3.4 Electron Beam Induced Current (EBIC) / 4.3.5 Cathodoluminescence (CL) / 4.3.6 Photoluminescence (PL)</i>	
4.4	Highlights of the Chapter	159
	References	159
	Problems	160
5	Growth of Bulk Crystals	162
5.1	Production of Starting Materials	162
	<i>5.1.1 Production of Electronic-Grade Polysilicon from Quartzite / 5.1.2 Synthesis of Polycrystalline Compound Semiconductor Source Materials</i>	
5.2	Growth of Bulk Crystals	165
	<i>5.2.1 Growth of Silicon Crystals / 5.2.1.1 Czochralski (CZ) process / 5.2.1.2 Float-zone (FZ) process / 5.2.1.3 Growth of silicon ribbons / 5.2.2 Compound Semiconductors / 5.2.2.1 Liquid-encapsulated Czochralski process / 5.2.2.2 Horizontal and vertical Bridgman techniques / 5.2.2.3 Effects of existence region on stoichiometry of crystals / 5.2.2.4 Growth of semiinsulating crystals</i>	
5.3	Sources of Dislocations in As-Grown Crystals and Perfection Enhancement	176
5.4	Doping in the Melt	186
	<i>5.4.1 Underlying Concepts / 5.4.1.1 Equilibrium and effective distribution coefficients of dopants / 5.4.1.2 k_{eq} and phase diagrams / 5.4.1.3 Interrelationship of k_{eq}, k_{eff}, and microscopic growth rate / 5.4.1.4 Solute concentration in the crystal as a function of melt fraction solidified / 5.4.2 Dopant or Impurity Striations</i>	
5.5	Microdefects in Macroscopically Dislocation-Free Silicon Crystals	200
	<i>5.5.1 Nature of Microdefects and Their Distribution</i>	

5.6	Oxygen Silicon	207
	<i>5.6.1 Basic Properties of Oxygen in Silicon / 5.6.2 Influence of Annealing on Electrical, Structural and Mechanical Characteristics / 5.6.2.1 Electrical characteristics / 5.6.2.2 Structural characteristics / 5.6.2.3 Mechanical properties / 5.6.2.4 Internal gettering of impurities by silicon-oxygen precipitates</i>	
5.7	Highlights of the Chapter	217
	References	217
	Problems	220
6	Epitaxial Growth	223
6.1	Epitaxial Growth Techniques	223
	<i>6.1.1 Liquid Phase Epitaxy / 6.1.1.1 Approximate mathematical treatment of step cooling and equilibrium cooling / 6.1.1.2 Choice of solvents / 6.1.1.3 In situ etching / 6.1.1.4 LPE systems and growth of multilayer structures / 6.1.1.5 Growth of doped layers / 6.1.1.6 Surface morphology of layers / 6.1.2 Vapor Phase Epitaxy / 6.1.2.1 Basics of VPE growth / 6.1.2.2 VPE of silicon and silicon-germanium layers / 6.1.2.3 VPE of compound semiconductors / 6.1.3 Molecular Beam Epitaxy / 6.1.3.1 Compound semiconductors / 6.1.3.2 Silicon and silicon-germanium</i>	
6.2	Epitaxial Growth on Patterned Substrates	260
6.3	Heteroepitaxy	263
6.4	Defects in Epitaxial Layers	268
	<i>6.4.1 Growth-Process-Independent Defects / 6.4.1.1 Threading dislocations / 6.4.1.2 Misfit dislocations / 6.4.1.3 Stacking faults and twins / 6.4.2 Growth-Process-Dependent Defects / 6.4.2.1 Melt-carryover-induced defects / 6.4.2.2 Formation of hillocks in VPE layers / 6.4.2.3 Oval-shape defects in MBE layers</i>	
6.5	Microstructures of Mixed III-V Epitaxial Layers	282
6.6	Highlights of the Chapter	291
	References	291
	Problems	294
7	Oxidation	298
7.1	Thermodynamics of Oxidation	298
7.2	Kinetics of Oxidation	303

7.3	The Structure of Silicon Dioxide	309
7.4	Volume Change on Oxidation and Stresses at Silicon-Silicon Dioxide Interfaces	312
7.5	Factors Affecting Oxidation Rates	313
	<i>7.5.1 Effects of Surface Orientation / 7.5.2 Influence of Dopants / 7.5.3 Effects of Halogens / 7.5.4 Effects of Pressure</i>	
7.6	Oxidation-Induced Defects	316
7.7	Charges Associated with the Silicon-Silicon Dioxide System	324
7.8	Other Topics on Oxidation	326
7.9	Nonthermal Oxidation Methods	328
7.10	Highlights of the Chapter	329
	References	329
	Problems	330
8	Diffusion	332
8.1	Description of Diffusion	332
	<i>8.1.1 Atomic Diffusion Mechanisms / 8.1.2 Phenomenological Description of Diffusion</i>	
8.2	Selective Doping by Diffusion	337
8.3	Dependence of Diffusion Coefficient on Temperature	344
8.4	Dependence of Diffusion Coefficient on Concentration	347
8.5	Dependence of Diffusion Coefficient on External Fields	350
8.6	Self-Diffusion in Semiconductors	352
8.7	Dopant Diffusion in Semiconductors	356
8.8	Diffusion of Electrically Active Contaminants	361
8.9	Diffusion of Carbon, Oxygen, and Hydrogen in Silicon	363
8.10	Sequential Diffusion	364
8.11	Oxidation-Induced Diffusion Enhancement or Retardation in Silicon	366
8.12	Diffusion in Polycrystalline Solids	368
8.13	Diffusion-Induced Dislocation Networks	369
8.14	Highlights of the Chapter	375
	References	375
	Problems	376

9 Ion Implantation	378
9.1 Ion Ranges and Implantation Profiles	378
<i>9.1.1 Theory of Ion Stopping / 9.1.2 Implantation Profiles in Amorphous Solids</i>	
9.2 Ion Channeling	384
9.3 Ion Implantation-Induced Damage and its Annealing Behavior	386
<i>9.3.1 Damage / 9.3.2 Annealing Behavior / 9.3.2.1 Isochronal annealing behavior of silicon implanted with boron ions / 9.3.2.2 Isochronal annealing behavior of silicon implanted with phosphorous ions / 9.3.2.3 Isochronal annealing behavior of GaAs implanted with Be ions / 9.3.2.4 Annealing Behavior of GaAs implanted with S and Se ions / 9.3.2.5 Semi-insulating GaAs by the implantation of hydrogen ions / 9.3.3 Diffusion of Implanted Impurities</i>	
9.4 Process Considerations	401
<i>9.4.1 Materials for Masks / 9.4.2 Multiple Implants / 9.4.3 Annealing Setups</i>	
9.5 Comparison of Ion Implantation and Diffusion for Selective Doping	404
9.6 Highlights of the Chapter	405
References	406
Problems	407
10 Metallization	408
10.1 Deposition of Thin Films for Contacts and Interconnects	408
<i>10.1.1 Physical Vapor Deposition (Evaporation) / 10.1.2 Sputtering / 10.1.3 Chemical Vapor Deposition</i>	
10.2 Microstructure of Thin Films	419
10.3 Contact Metallizations	427
<i>10.3.1 Films for Schottky Contacts / 10.3.2 Films for Ohmic Contacts</i>	
10.4 Consequences of Metal-Semiconductor Interactions	432
10.5 Diffusion Barriers	437
10.6 Films for Interconnects	438
10.7 Electromigration in Interconnects	440
10.8 Highlights of the Chapter	444
References	444
Problems	445

11 Lithography and Etching	448
11.1 Lithography	448
<i>11.1.1. Resists / 11.1.2 Masks / 11.1.3 Radiation Sources and Lithographies / 11.1.3.1 Optical and X-Ray Lithographies / 11.1.3.2 Electron- and ion-beam Lithographies</i>	
11.2 Etching	468
<i>11.2.1 Wet Etching / 11.2.2 Dry Etching</i>	
11.3 Highlights of the Chapter	480
References	481
Problems	481
 12 Challenges in Growth and Processing of Semiconductors	 483
12.1 Growth of Bulk Crystals of III-N Materials	484
12.2 Growth of Quantum Wells, Wires, and Dots	485
12.3 Thin Dielectrics	489
12.4 Formation of Shallow Junctions	491
12.5 Multilevel Interconnections for the ULSI and Gigabit Scale Integration (GSI) Eras	494
12.6 Direct Writing	496
References	499

Semiconductors: An Introduction

This chapter develops an introductory framework for understanding the behavior of semiconductors. It introduces the concepts of band gaps and charge carriers in semiconductors, that is, electrons and holes, discusses the changes in carrier concentration due to the addition of dopants, and correlates the conductivity of a semiconductor with the mobilities of the carriers. These concepts underlie the operation of semiconducting devices covered in Chapter 2.

1.1 BEHAVIOR OF FREE ELECTRONS

We show later in this chapter that the conduction in semiconductors occurs by the migration of two types of charge carriers, one of them being electrons. The presence of two types of carriers produces interesting effects in semiconductors. Therefore, we first discuss the properties of free electrons, that is, electrons that exist outside a solid—and progressively add more realism to this model so that it represents a semiconductor.

1.1.1 Particle-Wave Duality

Free electrons exhibit particle-wave duality. Figure 1.1 shows a setup to demonstrate the particle-like behavior. The electrons from a hot cathode overcome the surface potential barrier when a suitable potential is applied between the cathode and an anode. The anode has a pinhole that collimates the free-electron beam emitted from the cathode. When this beam hits a target metal, it ejects core-shell electrons from the atoms. An outer-shell electron rapidly fills the resulting vacancy in the core shell. The difference in the energies between the two electronic levels is given off as an X-ray photon. This behavior is consistent with the particle-like nature of electrons.

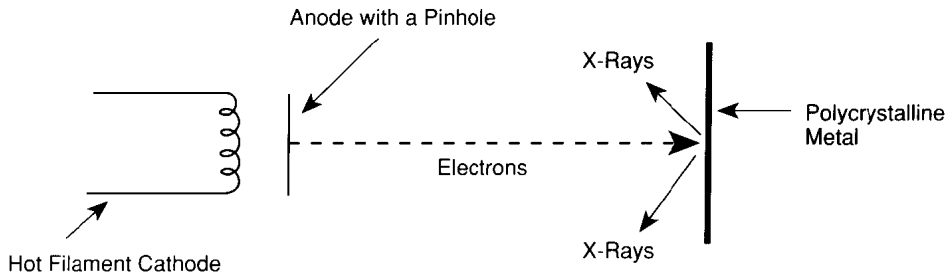


FIGURE 1.1
Schematic of a setup that can demonstrate the particle-like behavior of free electrons.

Now consider the setup shown in Figure 1.2. The electron beam defined by magnetic lenses traverses a very thin, single crystal sample and is Bragg diffracted. The diffraction produces a large number of diffraction spots on a fluorescent screen as shown in Figure 1.2. The pattern is best understood if the electrons behave as waves.

The equivalence between the particle- and wavelike behaviors of free electrons is provided by the Planck and de Broglie relations. According to Planck, electron energy E is related to its frequency ν by

$$\nu = \frac{E}{h}, \quad (1.1)$$

where h is Planck's constant. This relation is applicable to all types of electromagnetic radiation. On the other hand, de Broglie hypothesized that the wavelength λ of a wave associated with an electron is related to its momentum p by

$$\lambda = \frac{h}{p}. \quad (1.2)$$

Every particle can exhibit the particle- and wavelike behaviors. Whether the wavelike nature of a particle is experimentally discernible depends on the wave-

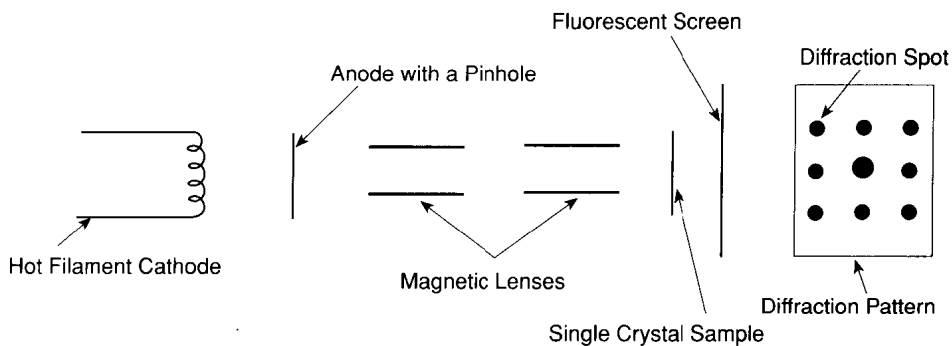


FIGURE 1.2
Schematic of a setup that can demonstrate the wave-like behavior of free electrons.

length of the wave associated with the particle relative to the dimension of the experiment. For electrons the mass is extremely small (9.11×10^{-31} kg). Therefore, for reasonable values of velocities, as shown in Example 1.1, the values of momentum are fairly small, resulting in associated wavelengths of waves that can be discerned by their diffraction from a grating consisting of lattice planes within a crystal.

EXAMPLE 1.1. Electrons are excited from a hot wire cathode at a potential of 100 kV. Calculate the wavelength of the electrons.

Solution

$$\begin{aligned} E = \text{the kinetic energy of the accelerated electrons} &= \frac{1}{2} mv^2 \\ &= 100 \text{ keV} \\ &= 1.6 \times 10^{-14} \text{ J.} \end{aligned}$$

$E = \frac{1}{2} mv^2$ is reasonable because E is much less than the rest energy mc^2 (500 keV), where c is the velocity of light. For higher energies you need to use the relativistic formulas.

$p = \text{momentum of the electrons} = \sqrt{2mE}$, where m is the mass of the electron (9.11×10^{-31} kg).

$$\begin{aligned} \text{Thus } p &= \sqrt{2 \times 9.11 \times 10^{-31} \times 1.6 \times 10^{-14}} \text{ kg-m/sec} \\ &= 1.7 \times 10^{-22} \text{ kg-m/sec.} \end{aligned}$$

According to de Broglie

$$\lambda = \frac{h}{p}.$$

Substituting for p and $h = 6.6 \times 10^{-34}$ J sec, we obtain

$$\lambda = \frac{6.6 \times 10^{-34}}{1.7 \times 10^{-22}} = 0.004 \text{ nm.}$$

Waves having the preceding wavelength can be diffracted from various lattice planes within silicon and gallium arsenide whose lattice parameters are 0.543 and 0.565 nm. Diffraction occurs because the electron wavelength is considerably smaller than the separations between different gratings formed by different crystal planes.

1.1.2 Uncertainty Principle

We cannot describe the events involving atomic particles with absolute precision. Instead, we must think of the average values of position, momentum, and energy of a particle such as an electron. According to Heisenberg, the uncertainties in the measurements of position Δx and momentum Δp are related by the uncertainty relation

$$(\Delta x)(\Delta p) \geq \hbar, \quad (1.3)$$