

# CONTENTS

Preface xiii

## Chapter 1

### Elementary Materials Science Concepts 3

- 1.1 Atomic Structure 3
- 1.2 Bonding and Types of Solids 7
  - 1.2.1 Molecules and General Bonding Principles 7
  - 1.2.2 Covalently Bonded Solids: Diamond 9
  - 1.2.3 Metallic Bonding: Copper 11
  - 1.2.4 Ionically Bonded Solids: Salt 12
  - 1.2.5 Secondary Bonding 15
  - 1.2.6 Mixed Bonding 18
- 1.3 Kinetic Molecular Theory 21
  - 1.3.1 Mean Kinetic Energy and Temperature 21
  - 1.3.2 Thermal Expansion 27
- 1.4 Molecular Velocity and Energy Distribution 30
- 1.5 Heat, Thermal Fluctuations, and Noise 34
- 1.6 Thermally Activated Processes 39
- 1.7 The Crystalline State 43
  - 1.7.1 Types of Crystals 43
  - 1.7.2 Crystal Directions and Planes 49
  - 1.7.3 Allotropy and the Three Phases of Carbon 54
- 1.8 Crystalline Defects and Their Significance 56
  - 1.8.1 Point Defects: Vacancies and Impurities 57
  - 1.8.2 Line Defects: Edge and Screw Dislocations 60
  - 1.8.3 Planar Defects: Grain Boundaries 63
  - 1.8.4 Crystal Surfaces and Surface Properties 64

1.8.5 Stoichiometry, Nonstoichiometry, and Defect Structures 66

1.9 Single-Crystal Czochralski Growth 67

1.10 Glasses and Amorphous Semiconductors 69

1.10.1 Glasses and Amorphous Solids 69

1.10.2 Crystalline and Amorphous Silicon 72

1.11 Solid Solutions and Two-Phase Solids 74

1.11.1 Isomorphous Solid Solutions: Isomorphous Alloys 74

1.11.2 Phase Diagrams: Cu–Ni and Other Isomorphous Alloys 75

1.11.3 Zone Refining and Pure Silicon Crystals 80

1.11.4 Binary Eutectic Phase Diagrams and Pb–Sn Solders 81

Additional Topics 86

1.12 Bravais Lattices 86

Defining Terms 89

Questions and Problems 93

## Chapter 2

### Electrical and Thermal Conduction in Solids 101

2.1 Classical Theory: The Drude Model 102

2.1.1 Metals and Conduction by Electrons 102

2.2 Temperature Dependence of Resistivity: Ideal Pure Metals 108

2.3 Matthiessen's Rule 111

2.3.1 Matthiessen's Rule and the Temperature Coefficient of Resistivity ( $\alpha$ ) 111

2.3.2 Solid Solutions and Nordheim's Rule 121

2.4 Mixture Rules and Electrical Switches 125

2.4.1 Heterogeneous Mixtures 125

2.4.2	Two-Phase Alloy (Ag–Ni) Resistivity and Electrical Contacts	128
2.5	The Hall Effect and Hall Devices	130
2.6	Thermal Conduction	134
2.6.1	Thermal Conductivity	134
2.6.2	Thermal Resistance	139
2.7	Electrical Conductivity of Nonmetals	140
2.7.1	Semiconductors	140
2.7.2	Ionic Crystals and Glasses	145
	Additional Topics	148
2.8	Skin Effect: HF Resistance of a Conductor	148
2.9	Thin Metal Films and Integrated Circuit Interconnections	152
	Defining Terms	154
	Questions and Problems	156

### Chapter 3

## Elementary Quantum Physics 163

3.1	Photons	163
3.1.1	Light as a Wave	163
3.1.2	The Photoelectric Effect	166
3.1.3	Compton Scattering	170
3.1.4	Black Body Radiation	172
3.2	The Electron as a Wave	175
3.2.1	De Broglie Relationship	175
3.2.2	Time-Independent Schrödinger Equation	178
3.3	Infinite Potential Well: A Confined Electron	182
3.4	Heisenberg's Uncertainty Principle	187
3.5	Tunneling Phenomenon: Quantum Leak	190
3.6	Potential Box: Three Quantum Numbers	197
3.7	Hydrogenic Atom	199
3.7.1	Electron Wavefunctions	199
3.7.2	Quantized Electron Energy	205
3.7.3	Orbital Angular Momentum and Space Quantization	208
3.7.4	Electron Spin and Intrinsic Angular Momentum $S$	213
3.7.5	Total Angular Momentum $J$	216
3.8	The Helium Atom and the Periodic Table	218

3.8.1	He Atom and Pauli Exclusion Principle	218
3.8.2	Hund's Rule	220
3.9	Stimulated Emission and Lasers	222
3.9.1	Stimulated Emission and Photon Amplification	222
3.9.2	Helium–Neon Laser	225
3.9.3	Laser Output Spectrum	228

### Additional Topics 231

### 3.10 Optical Fiber Amplifiers 231

### Defining Terms 233

### Questions and Problems 236

### Chapter 4

## Modern Theory of Solids 241

4.1	Hydrogen Molecule: Molecular Orbital Theory of Bonding	241
4.2	Band Theory of Solids	247
4.2.1	Energy Band Formation	247
4.2.2	Properties of Electrons in a Band	252
4.3	Semiconductors	255
4.4	Electron Effective Mass	259
4.5	Density of States in an Energy Band	261
4.6	Statistics: Collections of Particles	268
4.6.1	Boltzmann Classical Statistics	268
4.6.2	Fermi–Dirac Statistics	269
4.7	Quantum Theory of Metals	271
4.7.1	Free Electron Model	271
4.7.2	Conduction in Metals	274
4.8	Fermi Energy Significance	276
4.8.1	Metal–Metal Contacts: Contact Potential	276
4.8.2	The Seebeck Effect and the Thermocouple	278
4.9	Thermionic Emission and Vacuum Tube Devices	284
4.9.1	Thermionic Emission: Richardson–Dushman Equation	284
4.9.2	Schottky Effect and Field Emission	287
4.10	Phonons	291
4.10.1	Harmonic Oscillator and Lattice Waves	291

- 4.10.2 Debye Heat Capacity 296
- 4.10.3 Thermal Conductivity of Nonmetals 300
- 4.10.4 Electrical Conductivity 302
- Additional Topics 304
- 4.11 Band Theory of Metals: Electron Diffraction in Crystals 304
- Defining Terms 313
- Questions and Problems 315

## Chapter 5

### Semiconductors 321

- 5.1 Intrinsic Semiconductors 322
  - 5.1.1 Silicon Crystal and Energy Band Diagram 322
  - 5.1.2 Electrons and Holes 324
  - 5.1.3 Conduction in Semiconductors 326
  - 5.1.4 Electron and Hole Concentrations 328
- 5.2 Extrinsic Semiconductors 335
  - 5.2.1 *n*-Type Doping 336
  - 5.2.2 *p*-Type Doping 338
  - 5.2.3 Compensation Doping 340
- 5.3 Temperature Dependence of Conductivity 344
  - 5.3.1 Carrier Concentration Temperature Dependence 344
  - 5.3.2 Drift Mobility: Temperature and Impurity Dependence 349
  - 5.3.3 Conductivity Temperature Dependence 352
  - 5.3.4 Degenerate and Nondegenerate Semiconductors 354
- 5.4 Recombination and Minority Carrier Injection 355
  - 5.4.1 Direct and Indirect Recombination 355
  - 5.4.2 Minority Carrier Lifetime 358
- 5.5 Diffusion and Conduction Equations, and Random Motion 364
- 5.6 Continuity Equation 370
  - 5.6.1 Time-Dependent Continuity Equation 370
  - 5.6.2 Steady-State Continuity Equation 372
- 5.7 Optical Absorption 375
- 5.8 Luminescence 379
- 5.9 Schottky Junction 381
  - 5.9.1 Schottky Diode 381
  - 5.9.2 Schottky Junction Solar Cell 385
- 5.10 Ohmic Contacts and Thermoelectric Coolers 388
  - Additional Topics 393
- 5.11 Direct and Indirect Bandgap Semiconductors 393
- 5.12 Indirect Recombination 402
- Defining Terms 403
- Questions and Problems 406

## Chapter 6

### Semiconductor Devices 415

- 6.1 Ideal *pn* Junction 416
  - 6.1.1 No Applied Bias: Open Circuit 416
  - 6.1.2 Forward Bias: Diffusion Current 421
  - 6.1.3 Forward Bias: Recombination and Total Current 427
  - 6.1.4 Reverse Bias 429
- 6.2 *pn* Junction Band Diagram 434
  - 6.2.1 Open Circuit 434
  - 6.2.2 Forward and Reverse Bias 435
- 6.3 Depletion Layer Capacitance of the *pn* Junction 438
- 6.4 Diffusion (Storage) Capacitance and Dynamic Resistance 440
- 6.5 Reverse Breakdown: Avalanche and Zener Breakdown 442
  - 6.5.1 Avalanche Breakdown 443
  - 6.5.2 Zener Breakdown 444
- 6.6 Bipolar Transistor (BJT) 446
  - 6.6.1 Common Base (CB) dc Characteristics 446
  - 6.6.2 Common Base Amplifier 451
  - 6.6.3 Common Emitter (CE) dc Characteristics 456
  - 6.6.4 Low-Frequency Small-Signal Model 457
- 6.7 Junction Field Effect Transistor (JFET) 460
  - 6.7.1 General Principles 460

- 6.7.2 JFET Amplifier 467
- 6.8 Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET) 471
  - 6.8.1 Field Effect and Inversion 471
  - 6.8.2 Enhancement MOSFET 473
  - 6.8.3 Threshold Voltage 477
  - 6.8.4 Ion Implanted MOS Transistors and Poly-Si Gates 479
- 6.9 Light Emitting Diodes (LED) 481
  - 6.9.1 LED Principles 481
  - 6.9.2 Heterojunction High-Intensity LEDs 485
  - 6.9.3 LED Characteristics 486
- 6.10 Photovoltaic Device Principles 488  
Additional Topics 495
- 6.11 Semiconductor Optical Amplifiers and Lasers 495
- Defining Terms 497
- Questions and Problems 500

## Chapter 7

### Dielectric Materials and Insulation 507

- 7.1 Matter Polarization and Relative Permittivity 508
  - 7.1.1 Relative Permittivity: Definition 508
  - 7.1.2 Dipole Moment and Electronic Polarization 509
  - 7.1.3 Polarization Vector  $\mathbf{P}$  512
  - 7.1.4 Local Field  $\mathcal{E}_{loc}$  and Clausius–Mossotti Equation 515
- 7.2 Electronic Polarization: Covalent Solids 517
- 7.3 Polarization Mechanisms 519
  - 7.3.1 Ionic Polarization 519
  - 7.3.2 Orientational (Dipolar) Polarization 520
  - 7.3.3 Interfacial Polarization 523
  - 7.3.4 Total Polarization 524
- 7.4 Frequency Dependence: Dielectric Constant and Dielectric Loss 526
- 7.5 Gauss’s Law and Boundary Conditions 534

- 7.6 Dielectric Strength and Insulation Breakdown 540
  - 7.6.1 Dielectric Strength: Definition 540
  - 7.6.2 Dielectric Breakdown and Partial Discharges: Gases 541
  - 7.6.3 Dielectric Breakdown: Liquids 542
  - 7.6.4 Dielectric Breakdown: Solids 543
- 7.7 Capacitor Dielectric Materials 550
  - 7.7.1 Typical Capacitor Constructions 550
  - 7.7.2 Dielectrics: Comparison 554
- 7.8 Piezoelectricity, Ferroelectricity, and Pyroelectricity 557
  - 7.8.1 Piezoelectricity 557
  - 7.8.2 Piezoelectricity: Quartz Oscillators and Filters 563
  - 7.8.3 Ferroelectric and Pyroelectric Crystals 566
- Additional Topics 571
- 7.9 Electric Displacement and Depolarization Field 571
- Defining Terms 576
- Questions and Problems 579

## Chapter 8

### Magnetic Properties and Superconductivity 589

- 8.1 Magnetization of Matter 589
  - 8.1.1 Magnetic Dipole Moment 589
  - 8.1.2 Atomic Magnetic Moments 591
  - 8.1.3 Magnetization Vector  $\mathbf{M}$  592
  - 8.1.4 Magnetizing Field or Magnetic Field Intensity  $\mathbf{H}$  595
  - 8.1.5 Magnetic Permeability and Magnetic Susceptibility 596
- 8.2 Magnetic Material Classifications 600
  - 8.2.1 Diamagnetism 600
  - 8.2.2 Paramagnetism 602
  - 8.2.3 Ferromagnetism 603
  - 8.2.4 Antiferromagnetism 603
  - 8.2.5 Ferrimagnetism 604
- 8.3 Ferromagnetism Origin and the Exchange Interaction 604

- 8.4 Saturation Magnetization and Curie Temperature 607
  - 8.5 Magnetic Domains: Ferromagnetic Materials 609
    - 8.5.1 Magnetic Domains 609
    - 8.5.2 Magnetocrystalline Anisotropy 610
    - 8.5.3 Domain Walls 612
    - 8.5.4 Magnetostriction 613
    - 8.5.5 Domain Wall Motion 614
    - 8.5.6 Polycrystalline Materials and the  $M$  versus  $H$  Behavior 615
    - 8.5.7 Demagnetization 619
  - 8.6 Soft and Hard Magnetic Materials 621
    - 8.6.1 Definitions 621
    - 8.6.2 Initial and Maximum Permeability 622
  - 8.7 Soft Magnetic Materials: Examples and Uses 623
  - 8.8 Hard Magnetic Materials: Examples and Uses 626
  - 8.9 Superconductivity 631
    - 8.9.1 Zero Resistance and the Meissner Effect 631
    - 8.9.2 Type I and Type II Superconductors 634
    - 8.9.3 Critical Current Density 637
  - 8.10 Superconductivity Origin 640
  - Additional Topics 641
  - 8.11 Magnetic Recording Materials 641
  - 8.12 Josephson Effect 647
  - 8.13 Flux Quantization 649
  - Defining Terms 650
  - Questions and Problems 654
- Chapter 9**
- Optical Properties of Materials 663**
- 9.1 Light Waves in a Homogeneous Medium 664
  - 9.2 Refractive Index 667
  - 9.3 Dispersion: Refractive Index–Wavelength Behavior 669
  - 9.4 Group Velocity and Group Index 672
  - 9.5 Magnetic Field: Irradiance and Poynting Vector 675
  - 9.6 Snell’s Law and Total Internal Reflection (TIR) 677
  - 9.7 Fresnel’s Equations 680
    - 9.7.1 Amplitude Reflection and Transmission Coefficients 680
    - 9.7.2 Intensity, Reflectance, and Transmittance 685
  - 9.8 Complex Refractive Index and Light Absorption 690
  - 9.9 Lattice Absorption 694
  - 9.10 Band-to-Band Absorption 695
  - 9.11 Light Scattering in Materials 698
  - 9.12 Attenuation in Optical Fibers 699
  - 9.13 Polarization 702
  - 9.14 Optical Anisotropy 704
    - 9.14.1 Uniaxial Crystals and Fresnel’s Optical Indicatrix 705
    - 9.14.2 Birefringence of Calcite 708
    - 9.14.3 Dichroism 709
  - 9.15 Birefringent Retarding Plates 710
  - 9.16 Optical Activity and Circular Birefringence 712
  - Additional Topics 714
  - 9.17 Electro-optic Effects 714
  - Defining Terms 717
  - Questions and Problems 720
- Appendix A**
- Major Symbols and Abbreviations 724**
- Appendix B**
- Elements to Uranium 730**
- Appendix C**
- Constants and Useful Information 733**
- Index 795**