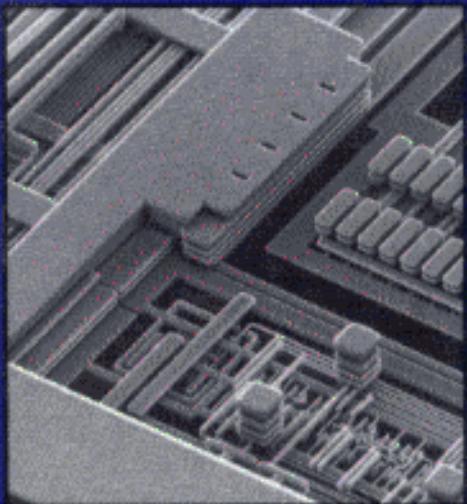
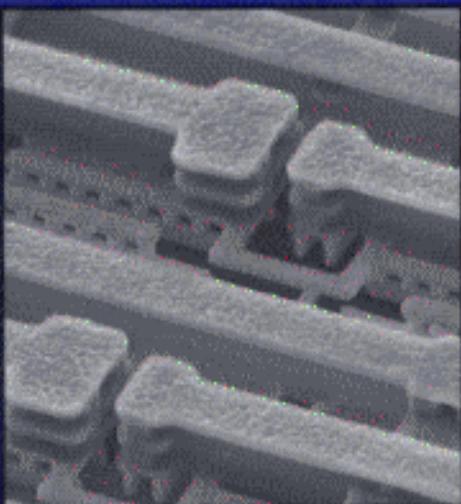


Second Edition

Principles of
**Electronic
Materials and
Devices**



S.O. Kasap

INTERNATIONAL EDITION

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 (α) 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	3.8.1	He Atom and Pauli Exclusion Principle	218
2.5	The Hall Effect and Hall Devices	130	3.8.2	Hund's Rule	220
2.6	Thermal Conduction	134	3.9	Stimulated Emission and Lasers	222
2.6.1	Thermal Conductivity	134	3.9.1	Stimulated Emission and Photon Amplification	222
2.6.2	Thermal Resistance	139	3.9.2	Helium–Neon Laser	225
2.7	Electrical Conductivity of Nonmetals	140	3.9.3	Laser Output Spectrum	228
2.7.1	Semiconductors	140		Additional Topics	231
2.7.2	Ionic Crystals and Glasses	145	3.10	Optical Fiber Amplifiers	231
	Additional Topics	148		Defining Terms	233
2.8	Skin Effect: HF Resistance of a Conductor	148		Questions and Problems	236
2.9	Thin Metal Films and Integrated Circuit Interconnections	152			
	Defining Terms	154	Chapter 4		
	Questions and Problems	156		Modern Theory of Solids	241
Chapter 3					
Elementary Quantum Physics 163					
3.1	Photons	163	4.1	Hydrogen Molecule: Molecular Orbital Theory of Bonding	241
3.1.1	Light as a Wave	163	4.2	Band Theory of Solids	247
3.1.2	The Photoelectric Effect	166	4.2.1	Energy Band Formation	247
3.1.3	Compton Scattering	170	4.2.2	Properties of Electrons in a Band	252
3.1.4	Black Body Radiation	172	4.3	Semiconductors	255
3.2	The Electron as a Wave	175	4.4	Electron Effective Mass	259
3.2.1	De Broglie Relationship	175	4.5	Density of States in an Energy Band	261
3.2.2	Time-Independent Schrödinger Equation	178	4.6	Statistics: Collections of Particles	268
3.3	Infinite Potential Well: A Confined Electron	182	4.6.1	Boltzmann Classical Statistics	268
3.4	Heisenberg's Uncertainty Principle	187	4.6.2	Fermi–Dirac Statistics	269
3.5	Tunneling Phenomenon: Quantum Leak	190	4.7	Quantum Theory of Metals	271
3.6	Potential Box: Three Quantum Numbers	197	4.7.1	Free Electron Model	271
3.7	Hydrogenic Atom	199	4.7.2	Conduction in Metals	274
3.7.1	Electron Wavefunctions	199	4.8	Fermi Energy Significance	276
3.7.2	Quantized Electron Energy	205	4.8.1	Metal–Metal Contacts: Contact Potential	276
3.7.3	Orbital Angular Momentum and Space Quantization	208	4.8.2	The Seebeck Effect and the Thermocouple	278
3.7.4	Electron Spin and Intrinsic Angular Momentum S	213	4.9	Thermionic Emission and Vacuum Tube Devices	284
3.7.5	Total Angular Momentum J	216	4.9.1	Thermionic Emission: Richardson–Dushman Equation	284
3.8	The Helium Atom and the Periodic Table	218	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	<i>n</i> -Type Doping	336
5.2.2	<i>p</i> -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 <i>pn</i> 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	<i>pn</i> 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 <i>pn</i> 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)	470
6.8.1	Field Effect and Inversion	470
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	9.4	Group Velocity and Group Index	672
8.5	Magnetic Domains: Ferromagnetic Materials	609	9.5	Magnetic Field: Irradiance and Poynting Vector	675
8.5.1	Magnetic Domains	609	9.6	Snell's Law and Total Internal Reflection (TIR)	677
8.5.2	Magnetocrystalline Anisotropy	610	9.7	Fresnel's Equations	680
8.5.3	Domain Walls	612	9.7.1	Amplitude Reflection and Transmission Coefficients	680
8.5.4	Magnetostriction	613	9.7.2	Intensity, Reflectance, and Transmittance	685
8.5.5	Domain Wall Motion	614	9.8	Complex Refractive Index and Light Absorption	690
8.5.6	Polycrystalline Materials and the M versus H Behavior	615	9.9	Lattice Absorption	694
8.5.7	Demagnetization	619	9.10	Band-to-Band Absorption	695
8.6	Soft and Hard Magnetic Materials	621	9.11	Light Scattering in Materials	698
8.6.1	Definitions	621	9.12	Attenuation in Optical Fibers	699
8.6.2	Initial and Maximum Permeability	622	9.13	Polarization	702
8.7	Soft Magnetic Materials: Examples and Uses	623	9.14	Optical Anisotropy	704
8.8	Hard Magnetic Materials: Examples and Uses	626	9.14.1	Uniaxial Crystals and Fresnel's Optical Indicatrix	705
8.9	Superconductivity	631	9.14.2	Birefringence of Calcite	708
8.9.1	Zero Resistance and the Meissner Effect	631	9.14.3	Dichroism	709
8.9.2	Type I and Type II Superconductors	634	9.15	Birefringent Retarding Plates	710
8.9.3	Critical Current Density	637	9.16	Optical Activity and Circular Birefringence	712
8.10	Superconductivity Origin	640	Additional Topics	714	
Additional Topics	641	9.17	Electro-optic Effects	714	
8.11	Magnetic Recording Materials	641	Defining Terms	717	
8.12	Josephson Effect	647	Questions and Problems	720	
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

Appendix A

Major Symbols and Abbreviations 724

Appendix B

Elements to Uranium 730

Appendix C

Constants and Useful Information 733

Index 735