

Contents

Part I Review of Fundamentals of Semiconductors

| | | |
|----------|---|----------|
| 1 | Semiconductor Materials: Their Properties, Applications, and Recent Advances | 3 |
| 1.1 | Importance of Electronic and Semiconducting Materials | 3 |
| 1.2 | Classification of Electrical and Electronic Materials, and Status of Semiconducting Materials | 4 |
| 1.2.1 | Conductors | 5 |
| 1.2.2 | Semiconductors | 6 |
| 1.2.3 | Dielectrics | 6 |
| 1.2.4 | Superconductors | 7 |
| 1.3 | Scope of Application of Semiconducting Materials | 7 |
| 1.4 | Electrons and Their Role in Semiconductivity | 9 |
| 1.4.1 | Valence Electrons | 9 |
| 1.5 | Classification of Materials on the Basis of Energy Gap (or Band) | 10 |
| 1.5.1 | Valence and Conduction Band, and Energy Gap | 11 |
| 1.5.2 | Comparison among Conductors, Semiconductors and Insulators | 12 |
| 1.6 | Introduction to Semiconducting Materials | 13 |
| 1.6.1 | Different Types of Semiconducting Materials | 14 |
| 1.6.2 | Merits of Semiconducting Materials | 15 |
| 1.6.3 | Characteristics of Semiconducting Materials | 15 |
| 1.6.4 | Semiconducting Devices and Their Working Principles | 16 |
| 1.7 | Element Form Semiconducting Materials | 16 |
| 1.7.1 | Silicon (Si) | 16 |
| 1.7.2 | Germanium (Ge) | 17 |
| 1.7.3 | Selenium (Se) | 17 |
| 1.7.4 | Antimony (Sb) | 19 |

| | | |
|--------|---|----|
| 1.7.5 | Other Elements | 19 |
| 1.7.6 | Comparison Between Silicon and Germanium. . . . | 19 |
| 1.8 | Formulated (Compound and Alloyed) Semiconductor Materials | 20 |
| 1.8.1 | Gallium Arsenide (GaAs) | 20 |
| 1.8.2 | Indium Antimonite (InSb). | 21 |
| 1.8.3 | Oxides, Sulphides, Hallides, Tellurides and Sellurides | 22 |
| 1.8.4 | Cadmium Sulphide (CdS). | 22 |
| 1.8.5 | Silicon Carbide (SiC). | 23 |
| 1.8.6 | Lead Sulphide (PbS) | 23 |
| 1.8.7 | Indium Arsenide (InAs) | 23 |
| 1.9 | Choicest Materials for Different Semiconductor Devices . . . | 24 |
| 1.10 | Spintronics and Spintronic Materials | 26 |
| 1.10.1 | Major Fields of Spintronic Research | 26 |
| 1.10.2 | Operational Mechanisms of Spintronic Devices . . . | 26 |
| 1.10.3 | Working Principle of Spintronic Devices | 27 |
| 1.10.4 | Emerging and Futuristic Spintronic Materials | 27 |
| 1.11 | Ferromagnetic Semiconductor | 27 |
| 1.12 | Emerging Wide Bandgap Semiconductors | 28 |
| 1.13 | Left Handed (LH) Materials | 28 |
| 1.13.1 | Single Negative Left-Handed Materials | 29 |
| 1.13.2 | Double Negative Left-Handed Materials. | 30 |
| 1.13.3 | Negative Index Metamaterials | 30 |
| 1.13.4 | Double Positive Medium | 30 |
| 1.14 | Manganese Semiconductor | 31 |
| 1.15 | Diluted Magnetic Semiconductor. | 31 |
| 1.16 | Silicon: The Semiconductor Used as Raw Material in Making ICs | 32 |
| 1.16.1 | Gallium Arsenide (GaAs) for Making Integrated Circuit. | 33 |
| 1.17 | Semiconducting Photocatalytic Materials in the Services of Pollution Free Environment | 34 |
| 1.18 | LED Stumps: The Advent of Semiconductors in Cricket . . . | 34 |
| 1.19 | Glimpse of Some Salient Semiconductors. | 35 |
| 1.20 | Solved Examples | 36 |
| | Review Questions. | 37 |
| | Objective Questions | 38 |
| | Answers | 39 |
| | References. | 40 |

| | | |
|----------|---|-----------|
| 2 | Overview of Crystals, Bonding, Imperfections, Atomic Models, Narrow and Wide Bandgap Semiconductors and, Semiconductor Devices | 41 |
| 2.1 | Crystal Structure | 41 |
| 2.2 | Bravais Crystal System | 42 |
| 2.3 | Miller Indices: The Crystallographic Notation of Atomic Planes | 43 |
| 2.3.1 | Determining the Miller Indices of a Given Plane | 45 |
| 2.3.2 | Family of Planes | 47 |
| 2.3.3 | Miller Indices: Crystallographic Notation of Atomic Crystal Directions | 48 |
| 2.3.4 | Family of Directions | 49 |
| 2.4 | Chemical (or Atomic) Bonding | 49 |
| 2.4.1 | Type of Bond in Semiconductors | 49 |
| 2.4.2 | Nature of Bond in Semiconductors | 50 |
| 2.5 | Bonding Forces. | 50 |
| 2.5.1 | Bonding Length and Bond Forces | 51 |
| 2.6 | Covalent Bond and Semiconductors. | 52 |
| 2.6.1 | Type of Covalent Bond in Semiconductors. | 52 |
| 2.6.2 | Bond Angle in Semiconductors. | 52 |
| 2.6.3 | Mixed Bond in Compound Semiconductors | 53 |
| 2.7 | Diamond Cubic (DC) Structure of Silicon and Germanium | 54 |
| 2.8 | Lattice Structures of Some Compound Semiconductors | 55 |
| 2.9 | Lattice Structure of Zinc Sulphide. | 56 |
| 2.10 | Crystal Imperfections. | 56 |
| 2.10.1 | Types of Imperfections. | 57 |
| 2.10.2 | Point Imperfections | 57 |
| 2.11 | Bohr's Quantum Atomic Model | 58 |
| 2.11.1 | Radii of Orbits, Velocity and Frequency of Electrons | 59 |
| 2.11.2 | Normal, Excited and Ionized Atoms | 59 |
| 2.11.3 | Electron Energy | 60 |
| 2.11.4 | Frequency of Radiation and Spectral Series of Hydrogen | 61 |
| 2.12 | Sommerfeld's Relativistic Atomic Model | 63 |
| 2.13 | Modern Concept of Atomic Model | 65 |
| 2.14 | Quantum States. | 67 |
| 2.14.1 | Pauli's Exclusion Principle | 67 |
| 2.15 | Important Applications of Semiconductor Devices. | 68 |
| 2.15.1 | Brief Description of Some Semiconductor Devices | 69 |

| | | |
|----------|---|-----------|
| 2.16 | Narrow Bandgap Semiconductor Materials | 70 |
| 2.16.1 | HgCdTe as Narrow Bandgap Semiconductor. | 71 |
| 2.16.2 | Applications as Infrared Detectors | 72 |
| 2.16.3 | Ternary Stannide Phase Narrow Bandgap Semiconductors: Na_2MgSn | 72 |
| 2.17 | Wide Bandgap Semiconductor | 74 |
| 2.17.1 | Advances in Wide Bandgap Materials for Semiconductor Spintronics. | 74 |
| 2.17.2 | Future Aspect of Wide Bandgap Materials Power Generating Window | 75 |
| 2.17.3 | Recent Advances in Wide Bandgap Materials | 76 |
| 2.18 | Rectifiers | 76 |
| 2.18.1 | Selenium Rectifier | 76 |
| 2.19 | Solved Examples | 77 |
| | Review Questions | 79 |
| | Numerical Problems | 81 |
| | Objective Questions | 83 |
| | Answers | 85 |
| | References. | 85 |
| 3 | Carrier Transport in Semiconductors | 87 |
| 3.1 | Electrons and Their Role in Conductivity | 87 |
| 3.1.1 | Valence Electrons | 88 |
| 3.1.2 | Free Electrons | 88 |
| 3.2 | Electron Theories of Solids | 88 |
| 3.2.1 | Free Electron Theory | 89 |
| 3.2.2 | Mechanism of Conduction by Free Electrons | 90 |
| 3.3 | Energy Band Theory | 91 |
| 3.4 | Brillouin Zone Theory | 93 |
| 3.4.1 | Meaning of Brillouin Zones | 94 |
| 3.4.2 | First and Second Brillouin Zones | 95 |
| 3.4.3 | Brillouin Zones for Simple Cubic Lattice | 96 |
| 3.4.4 | Brillouin Zones for BCC, FCC and HCP Lattices | 97 |
| 3.5 | Direct and Indirect Energy Band Semiconductors | 98 |
| 3.5.1 | Differences Between Direct and Indirect Semiconductors. | 99 |
| 3.5.2 | Variation of E_g with Alloy Composition. | 100 |
| 3.5.3 | Effect of Alloying on $\text{GaAs}_{1-x}\text{P}_x$ | 100 |
| 3.5.4 | Charge Carriers in Semiconductors | 102 |
| 3.5.5 | Fermi Energy Level. | 102 |
| 3.5.6 | Fermi-Dirac Probability Distribution | 103 |
| 3.6 | Intrinsic Semiconductors | 104 |
| 3.6.1 | Energy Diagram | 105 |
| 3.6.2 | Holes, Mobility and Conductivity | 106 |

| | | |
|----------|---|------------|
| 3.7 | Extrinsic Semiconductors | 108 |
| 3.7.1 | n-Type Semiconductors and Their Energy Diagram | 108 |
| 3.7.2 | p-Type Semiconductors and Their Energy Diagram | 109 |
| 3.8 | Effective Mass | 112 |
| 3.9 | Carrier Concentrations | 112 |
| 3.9.1 | Density of State, and Electron and Hole Concentration at Equilibrium | 113 |
| 3.10 | Temperature Dependency of Carrier Concentrations. | 116 |
| 3.10.1 | Temperature Dependency of n_i | 117 |
| 3.11 | Drift of Carriers in Electric and Magnetic Fields. | 118 |
| 3.11.1 | Drift Velocity and Collision Time | 118 |
| 3.11.2 | Mean Free Path (or Mean Free Length) and Conductivity | 121 |
| 3.12 | Effects of Temperature on Mobility of Carriers. | 121 |
| 3.12.1 | Effects of Doping on Mobility | 122 |
| 3.13 | Degenerate Semiconductors | 123 |
| 3.13.1 | Effect of Heavy Doping | 123 |
| 3.13.2 | Degenerate Types | 124 |
| 3.13.3 | Filled and Empty Energy States in Conventional and Degenerate Semiconductors | 124 |
| 3.14 | High-Field Effects. | 126 |
| 3.15 | The Hall Effect. | 126 |
| 3.15.1 | Significance of Hall Effect | 127 |
| 3.16 | Relation Between Density of States and Fermi Energy. | 131 |
| 3.16.1 | Quantization of Energy i.e. 3-dimensionalization. | 132 |
| 3.16.2 | Momentum Space | 132 |
| 3.16.3 | Fermi Sphere | 132 |
| 3.16.4 | Derivation of Different Fermi Parameters | 133 |
| 3.16.5 | Relation Among Density of Fermi States (E_F), E_F and N | 134 |
| 3.17 | Solved Examples | 137 |
| | Review Questions. | 140 |
| | Numerical Problems | 141 |
| | Objective Type Questions | 142 |
| | Answers | 143 |
| | Reference | 144 |
| 4 | Excess Carriers in Semiconductors | 145 |
| 4.1 | Introduction | 145 |
| 4.2 | Optical Absorption | 146 |
| 4.2.1 | Mechanism. | 147 |
| 4.2.2 | Absorption Coefficient. | 147 |

| | | |
|--------|---|-----|
| 4.2.3 | Factors Affecting the Absorption Coefficient. | 149 |
| 4.2.4 | Capability of a Material to Absorb Light | 152 |
| 4.3 | Luminescence. | 152 |
| 4.3.1 | Photo-Luminescence | 153 |
| 4.4 | Phosphorescence | 153 |
| 4.4.1 | Phosphorescence Materials | 154 |
| 4.4.2 | Mechanism of Excitation and Recombination in Photo-Luminescence | 154 |
| 4.5 | Electro-Luminescence | 155 |
| 4.5.1 | Examples of Electroluminescent Materials | 156 |
| 4.5.2 | Practical Implementations | 156 |
| 4.5.3 | Advantageous Features. | 157 |
| 4.6 | Carrier Lifetime | 158 |
| 4.7 | Derivation of Carrier Lifetime in Direct Recombination Mechanism. | 158 |
| 4.7.1 | Assumptions and Simplifications | 159 |
| 4.7.2 | Solution of Equation to Determine Lifetime | 160 |
| 4.7.3 | Generalization of Expression. | 160 |
| 4.8 | Indirect Recombination (i.e. Capture or Trapping Process). | 161 |
| 4.9 | Steady State Carrier Generation | 162 |
| 4.9.1 | Quasi-Fermi Levels | 163 |
| 4.10 | Photoconductivity | 164 |
| 4.10.1 | Applications of Photoconductive Devices | 164 |
| 4.10.2 | Photoconductive Materials and Factors Affecting Their Selection | 165 |
| 4.10.3 | Factors Affecting the Selection of Semiconductor | 166 |
| 4.11 | Photoconductive Cell. | 167 |
| 4.11.1 | Photo-Multiplier Tube | 167 |
| 4.12 | Diffusion of Carriers | 168 |
| 4.12.1 | Determining the Rate of Electron and Hole Diffusion | 169 |
| 4.12.2 | Analysis of Drift and Diffusion Carriers. | 171 |
| 4.13 | Einstein Relation. | 172 |
| 4.14 | Continuity Equation (i.e. Diffusion and Recombination). | 173 |
| 4.14.1 | Diffusion Equation and Diffusion Length | 174 |
| 4.15 | Transport of Charges and Impurity Distribution Profile During Diffusion. | 175 |
| 4.15.1 | Solution by Error Function Method | 175 |
| 4.15.2 | Complementary Error Function and Gaussian Distribution | 176 |

| | | |
|--------|--|-----|
| 4.16 | Long Diode and Short Diode | 179 |
| 4.16.1 | Voltage-Variable Capacitance | 180 |
| 4.16.2 | Effect of Dielectric Constant on Width of the Transition Region and Voltage Capacitance | 180 |
| 4.17 | Solved Examples | 181 |
| | Review Questions | 186 |
| | Numerical Problems | 187 |
| | Objective Questions | 188 |
| | Answers | 189 |
| | References | 189 |

Part II Junction and Interfaces

| | | |
|----------|--|------------|
| 5 | P-N Junctions and Their Breakdown Mechanisms | 193 |
| 5.1 | Junction Diode | 193 |
| 5.1.1 | P-N Diode (or P-N Junction Diode) | 194 |
| 5.1.2 | Applications of P-N Diode | 194 |
| 5.2 | Equilibrium Conditions | 195 |
| 5.2.1 | Electrostatic (or Contact) Potential | 195 |
| 5.2.2 | Establishing the Relation Between Contact Potential and Doping Concentrations | 197 |
| 5.3 | Fermi Level at Equilibrium | 199 |
| 5.3.1 | Space Charge at Junction | 201 |
| 5.3.2 | Determining the Maximum Value of Electric Field | 202 |
| 5.4 | Determining the Width of Depletion Region and Penetration Depth | 203 |
| 5.4.1 | Determining the Penetration Depth in Depletion Region | 204 |
| 5.5 | Biased Junctions | 206 |
| 5.6 | Working of p-n Diode When not Connected to a Battery | 208 |
| 5.6.1 | Diffusion of Holes and Electrons | 208 |
| 5.6.2 | Set-Up of Barrier | 208 |
| 5.6.3 | Formation of Depletion (or Space Charge) Region | 208 |
| 5.6.4 | Flow of Drift and Diffusion Current | 209 |
| 5.7 | Forward Biased p-n Junction | 209 |
| 5.7.1 | Voltage-Current Characteristics | 210 |
| 5.7.2 | Voltage-Ampere Equation and Its Temperature Dependence | 210 |
| 5.8 | Reverse Biased P-N Junction | 211 |
| 5.8.1 | Reverse-Bias Characteristics of a p-n Diode | 212 |
| 5.8.2 | Reverse Saturation Current | 213 |

| | | |
|----------|--|------------|
| 5.9 | Comparison of the Effects of No-bias, Forward-Bias and Reverse-Bias at a P-N Junction | 214 |
| 5.9.1 | Diode Equation | 214 |
| 5.9.2 | Poisson's Equation | 215 |
| 5.10 | Volt-Ampere Characteristics | 215 |
| 5.10.1 | In Forward Biasing | 215 |
| 5.10.2 | In Reverse Biasing | 216 |
| 5.11 | Junction Breakdown Mechanisms | 217 |
| 5.11.1 | Zener Breakdown | 217 |
| 5.11.2 | Avalanche Breakdown | 218 |
| 5.12 | Junction Capacitance | 219 |
| 5.13 | Rectifying Diodes | 219 |
| 5.13.1 | Half-Wave Rectifier | 220 |
| 5.13.2 | Full-Wave Rectifier | 221 |
| 5.14 | Zener Diode | 222 |
| 5.14.1 | Zener Diode for Meter Protection | 222 |
| 5.14.2 | Zener Diode as Peak Clipper | 223 |
| 5.15 | The Breakdown Diode | 224 |
| 5.15.1 | Use of Diodes in DC Power Supplies | 224 |
| 5.16 | Solved Examples | 225 |
| | Review Questions | 229 |
| | Numerical Problems | 231 |
| | Objective Questions | 231 |
| | Answers | 234 |
| | Reference | 234 |
| 6 | Different Types of Diodes, Ideal and Real Diodes, Switching Diodes, Abrupt and Graded Junctions | 235 |
| 6.1 | Examples of Diodes | 235 |
| 6.1.1 | Zener Diodes | 236 |
| 6.1.2 | Avalanche Diodes | 236 |
| 6.1.3 | Cat's Whisker (or Crystal) Diodes | 236 |
| 6.1.4 | Thermal Diodes | 237 |
| 6.1.5 | Constant Current Diodes | 237 |
| 6.1.6 | Photodiodes | 237 |
| 6.1.7 | PIN Diodes | 237 |
| 6.1.8 | Schottky Diodes | 238 |
| 6.1.9 | Gold-Doped Diodes | 238 |
| 6.1.10 | Super Barrier Diodes | 238 |
| 6.1.11 | Varicap (or Varactor) Diodes | 238 |
| 6.1.12 | Gunn Diodes | 239 |
| 6.1.13 | Esaki (or Tunnel) Diodes | 239 |
| 6.1.14 | Light-Emitting Diodes (LEDs) | 239 |
| 6.1.15 | Laser Diodes | 239 |

| | | |
|--------|--|-----|
| 6.1.16 | Transient Voltage Suppression (TVS) Diode | 240 |
| 6.1.17 | Snap-Off (or Step Recovery) Diodes (SRD) | 240 |
| 6.2 | Symbolic Representation of Different Diodes | 240 |
| 6.3 | The Diode Model | 241 |
| 6.4 | Real Diodes | 242 |
| 6.4.1 | Ideal Diode Versus Real Diode | 243 |
| 6.5 | Different Conditions of the Working of P-N Junctions | 244 |
| 6.6 | Transient Conditions | 244 |
| 6.7 | Time Dependent Variation in Space Charge | 245 |
| 6.7.1 | Determining the Solution for Stored Charge | 246 |
| 6.8 | Reverse Recovery Transient | 247 |
| 6.9 | Switching Diodes | 248 |
| 6.9.1 | Improving the Switching Speed | 248 |
| 6.9.2 | Narrow Base Diode | 249 |
| 6.10 | Capacitance of P-N Junctions | 249 |
| 6.10.1 | Derivation of the Expression for Junction Capacitance | 250 |
| 6.11 | Linearly Graded, Abrupt and Hyperabrupt Junctions | 251 |
| 6.11.1 | Doping Profile | 252 |
| 6.12 | Graded Junctions | 253 |
| 6.13 | Solved Examples | 255 |
| | Review Questions | 257 |
| | Objective Questions | 258 |
| | Answers | 259 |
| | Reference | 259 |

Part III Majority Carrier Diodes, Microwave Diodes, and Optoelectronic Devices

| | | |
|----------|---|------------|
| 7 | Majority Carrier Diodes (Tunnel Diode, Backward Diode, Schottky Barrier Diode, Ohmic Contacts, and Heterojunctions). | 263 |
| 7.1 | Introduction to Microwave Devices | 263 |
| 7.2 | Tunnel Diodes | 264 |
| 7.3 | Tunnel Diode Operation | 265 |
| 7.3.1 | Equilibrium or Zero-Bias Condition | 265 |
| 7.3.2 | Small Reverse Bias Condition | 266 |
| 7.3.3 | Small Forward Bias Condition | 266 |
| 7.3.4 | Increased Forward Bias Condition | 267 |
| 7.4 | Response of a Tunnel Diode Beyond the Negative Resistance Region | 267 |
| 7.5 | Total Tunnel Diode Characteristic | 268 |

| | | |
|----------|--|------------|
| 7.6 | Transit Time Device | 269 |
| 7.6.1 | Transit Time Effects | 269 |
| 7.6.2 | Requirements of a Good Transit Time Device. | 269 |
| 7.7 | The Backward Diode. | 270 |
| 7.7.1 | I-V Characteristics of Backward Diode. | 270 |
| 7.7.2 | Applications of Backward Diode. | 271 |
| 7.8 | Metal-Semiconductor Junctions. | 271 |
| 7.9 | Schottky Diodes | 271 |
| 7.9.1 | Case I: Mechanism of Schottky Diode When the Semiconductor Is of n-Type. | 272 |
| 7.9.2 | Case II: Mechanism of Schottky Diode When the Semiconductor Is of p-Type. | 273 |
| 7.9.3 | Limitations of Schottky Barrier Junctions. | 273 |
| 7.9.4 | Characteristics of Schottky Diode | 274 |
| 7.9.5 | Applications | 276 |
| 7.10 | Ohmic Contacts | 277 |
| 7.11 | Heterojunctions. | 277 |
| 7.11.1 | Unique Behaviour of Heterojunctions. | 278 |
| 7.11.2 | Band Discontinuities and Band Bending. | 279 |
| 7.12 | Potential Well in Heterojunction | 281 |
| | Review Questions. | 282 |
| 8 | Microwave Diodes (Varactor Diode, p-i-n Diode, IMPATT Diode, TRAPATT Diode, BARITT Diode, etc.) | 285 |
| 8.1 | Varactor Diode | 285 |
| 8.1.1 | V-I Characteristics of Varactor Diode | 286 |
| 8.1.2 | Performance Characteristics of Varactor Diode | 287 |
| 8.1.3 | Applications of Varactor Diodes | 289 |
| 8.2 | Photodiodes | 289 |
| 8.2.1 | Basic Construction of a Photodiode. | 290 |
| 8.2.2 | p-n Photodiode | 291 |
| 8.2.3 | p-i-n Photodiode | 292 |
| 8.2.4 | Avalanche Photodiode | 293 |
| 8.2.5 | Mid-Infrared Photodiodes | 295 |
| 8.3 | The IMPATT Diode | 295 |
| 8.3.1 | Operational Mechanism | 296 |
| 8.4 | Trapatt Diode | 296 |
| 8.4.1 | Plasma Formation in TRAPATT Diode | 297 |
| 8.4.2 | Operation | 297 |
| 8.4.3 | Advantages. | 298 |
| 8.4.4 | Applications of TRAPATT Devices. | 298 |
| 8.5 | BARITT Diode. | 298 |
| 8.5.1 | Structure of BARITT Diode | 298 |
| 8.5.2 | Performance of BARITT Diode. | 299 |

| | | |
|----------|---|------------|
| 8.6 | Transferred Electron Mechanism | 299 |
| 8.6.1 | Valleys in Conduction Band | 299 |
| 8.6.2 | Negative Differential Conductivity | 300 |
| 8.6.3 | Dependence of Electron Velocity on Electric Field | 300 |
| 8.7 | The Gunn Diode | 301 |
| 8.7.1 | Materials and Fabrication | 302 |
| 8.7.2 | Dielectric Relaxation Time in Respect of the Gunn Diode | 303 |
| 8.7.3 | Dependence of Electron Drift Velocity on Electric Field for a Gunn Diode | 303 |
| 8.8 | Dovett Diode | 304 |
| 8.9 | Solved Examples | 304 |
| | Review Questions | 306 |
| | Objective Questions | 307 |
| | Answers | 309 |
| 9 | Optoelectronic Devices | 311 |
| 9.1 | Introduction to Optoelectronic Devices | 311 |
| 9.1.1 | Salient Applications | 312 |
| 9.1.2 | Optoelectronic Semiconductor Devices | 313 |
| 9.2 | Optical Properties | 315 |
| 9.2.1 | Current and Voltage Characteristics of an Illuminated Junction | 315 |
| 9.3 | Solar Cells | 317 |
| 9.3.1 | Working Principle | 317 |
| 9.3.2 | Construction and Working | 317 |
| 9.4 | Factors Affecting the Efficiency of Solar Cells | 319 |
| 9.4.1 | Effect of Energy Gaps | 319 |
| 9.4.2 | Effect of Absorber | 319 |
| 9.4.3 | Effect of Diffusion Length | 320 |
| 9.5 | Solar Cell Fabrication and Materials | 320 |
| 9.5.1 | Advantages and Limitations of Solar Cells | 321 |
| 9.5.2 | Applications of Solar Cells | 321 |
| 9.5.3 | Importance of Fill Factor in Design of Solar Cell | 322 |
| 9.6 | Photodetectors | 322 |
| 9.6.1 | Working Principle | 323 |
| 9.6.2 | Requirements of a Good Photodetector | 324 |
| 9.6.3 | Method to Achieve a Fast Responding Speed | 324 |
| 9.7 | Different Types of Photodetectors | 325 |
| 9.7.1 | Construction of a p-i-n Photodetector | 325 |
| 9.7.2 | Construction of a Silicon Heterointerface Photodetector (SHIP) | 326 |

| | | |
|--------|--|-----|
| 9.7.3 | Photoconductive Detector | 326 |
| 9.7.4 | Choice of Materials for Photodetectors | 328 |
| 9.8 | Light Emitting Diodes | 328 |
| 9.8.1 | Construction and Working of LED | 328 |
| 9.8.2 | Construction of a LED for Fibre-Optic System . . . | 329 |
| 9.8.3 | Advantages, Applications and Specifications of LEDs | 330 |
| 9.8.4 | Light Emitting Materials. | 330 |
| 9.8.5 | A New Generation LED: Gallium Nitride Based Light Emitting Diodes | 332 |
| 9.9 | Semiconductor Lasers | 333 |
| 9.9.1 | Classification of Lasers | 333 |
| 9.9.2 | Merits of Semiconductor Lasers | 334 |
| 9.9.3 | Characteristics and Working | 334 |
| 9.9.4 | Properties of Laser Light | 335 |
| 9.9.5 | Laser Applications. | 336 |
| 9.9.6 | Materials for Semiconductor Lasers | 337 |
| 9.9.7 | Homojunction Laser and Hetero-Junction Laser. . . | 338 |
| 9.10 | Laser Diode | 338 |
| 9.11 | Light Dependent Resistors (LDRs) | 339 |
| 9.12 | Overlight Detector. | 340 |
| 9.13 | Phototransistor | 341 |
| 9.13.1 | Differences between Phototransistor and Photodiode | 341 |
| 9.14 | Solved Examples | 343 |
| | Review Questions | 347 |
| | Objective Questions | 348 |
| | Answers | 350 |
| | References. | 350 |

Part IV BJT and FET Transistors, and Power Devices

| | | |
|-----------|--|------------|
| 10 | Bipolar Junction Transistors | 353 |
| 10.1 | Introduction | 353 |
| 10.1.1 | Types of Transistors | 354 |
| 10.2 | Bipolar Junction Transistor (BJT) | 354 |
| 10.2.1 | Construction of BJT | 354 |
| 10.3 | Fundamentals of BJT Operation | 357 |
| 10.3.1 | Transistor Biasing | 359 |
| 10.3.2 | Transistor Currents | 360 |
| 10.4 | Transistor Circuit Configurations and Their Characteristics | 361 |
| 10.4.1 | Common-Base (CB) Characteristics | 362 |
| 10.4.2 | Common-Emitter (CE) Configuration. | 366 |

| | | |
|-----------|---|------------|
| 10.5 | Comparison Between CB, CE and CC Configurations | 370 |
| 10.6 | Amplification with BJTs | 370 |
| 10.6.1 | Amplification with CB Configuration. | 371 |
| 10.6.2 | Amplification with CE Configuration. | 372 |
| 10.6.3 | Amplification with CC Configuration. | 373 |
| 10.6.4 | Phase Reversal in Amplifiers | 374 |
| 10.7 | BJT Fabrication | 375 |
| 10.7.1 | Diffused Junction Transistors | 375 |
| 10.8 | Solved Examples | 375 |
| | Review Questions. | 379 |
| | Numerical Problems | 380 |
| | Objective Questions | 382 |
| | Answers | 383 |
| | Reference | 383 |
| 11 | Metal Semiconductor Field Effect Transistors, MOS Transistors, and Charge Coupled Device | 385 |
| 11.1 | Introduction | 385 |
| 11.2 | Field-Effect Transistor (FET) | 386 |
| 11.2.1 | Applications of FETs. | 386 |
| 11.3 | Metal-Semiconductor Field-Effect Transistors (MESFET). . . | 388 |
| 11.4 | Basic Construction of MESFETs. | 388 |
| 11.4.1 | Basic Types of MESFETs | 389 |
| 11.5 | High Frequency Performance | 390 |
| 11.6 | Models for I-V Characteristics of Short Channel MESFET. | 390 |
| 11.7 | Operation of MESFET. | 391 |
| 11.8 | Construction of MESFET Structure | 392 |
| 11.9 | Insulated-Gate Field-Effect Transistor (IGFET) | 393 |
| 11.10 | MOSFET. | 393 |
| 11.10.1 | Basic Types of MOSFETs | 393 |
| 11.11 | Construction of MOSFET | 394 |
| 11.12 | Operating Principle and I-V Characteristics of Enhancement Type n-Channel MOSFET | 395 |
| 11.13 | p-Channel Enhancement MOSFET (PMOS) | 396 |
| 11.13.1 | Characteristics. | 396 |
| 11.13.2 | Symbols for Enhancement MOSFET | 396 |
| 11.14 | Depletion Type MOSFET | 398 |
| 11.14.1 | Operation of n-Channel Depletion MOSFET. | 399 |
| 11.14.2 | Depletion Mode of Operation | 399 |
| 11.14.3 | Enhancement Mode of Operation | 401 |
| 11.14.4 | Characteristics of n-Channel Depletion MOSFET. | 401 |
| 11.14.5 | p-channel Depletion MOSFET and Its Characteristics | 402 |

| | | |
|-----------|---|------------|
| 11.15 | Symbols of Depletion MOSFET | 404 |
| 11.16 | Comparison Between n-channel and p-channel MOSFET . . . | 404 |
| 11.17 | Comparison Between DMOSFETs and EMOSFETs | 404 |
| 11.18 | Comparison Between FETs and BJTs | 405 |
| 11.19 | Short-Channel Effects | 406 |
| 11.20 | A Charge Coupled Device | 408 |
| 11.20.1 | Operation | 409 |
| 11.20.2 | Salient Uses | 409 |
| 11.21 | Solved Examples | 410 |
| | Review Questions | 412 |
| | Objective Questions | 413 |
| | Answers | 414 |
| | References | 414 |
| 12 | Power Semiconductor Devices | 415 |
| 12.1 | Introduction | 415 |
| 12.1.1 | Different Types of Power Semiconducting Devices | 416 |
| 12.1.2 | Four Layer Devices | 416 |
| 12.2 | P-N-P-N Diode | 417 |
| 12.2.1 | Conduction Mechanisms | 417 |
| 12.2.2 | The Two-Transistor Analogy | 418 |
| 12.2.3 | Variation of α with Injection | 419 |
| 12.2.4 | Current Transport Mechanism in Forward-Blocking State of P-N-P-N Diode | 420 |
| 12.2.5 | Current Transport Mechanism in Forward Conducting State of P-N-P-N Diode | 421 |
| 12.2.6 | Triggering Mechanisms | 421 |
| 12.3 | Silicon Controlled Rectifier (SCR) | 422 |
| 12.3.1 | Biasing of SCR | 423 |
| 12.3.2 | Operation of SCR | 424 |
| 12.3.3 | Firing (or Triggering) of an SCR | 424 |
| 12.3.4 | Turning OFF of SCR | 425 |
| 12.4 | Silicon Controlled Switch (SCS) | 425 |
| 12.4.1 | Mechanism | 426 |
| 12.4.2 | Applications | 427 |
| 12.5 | Applications of SCR | 427 |
| 12.5.1 | Half-Wave Power Control | 427 |
| 12.5.2 | Full-Wave Power Control | 428 |
| 12.6 | Bilateral Devices | 429 |
| 12.7 | Diac | 429 |
| 12.7.1 | Working | 431 |
| 12.7.2 | V-I Characteristics | 431 |
| 12.7.3 | Applications | 431 |

| | | |
|---------|---|-----|
| 12.8 | Triac | 432 |
| 12.8.1 | Construction | 432 |
| 12.8.2 | Working. | 432 |
| 12.8.3 | V-I Characteristics. | 434 |
| 12.8.4 | Applications | 434 |
| 12.9 | Insulated Gate Bipolar Transistor (IGBT). | 434 |
| 12.9.1 | Construction | 434 |
| 12.9.2 | Characteristics. | 436 |
| 12.9.3 | Advantageous Features of IGBT | 437 |
| 12.10 | High Frequency Thyristors | 437 |
| 12.10.1 | Silicon Carbide Thyristors | 437 |
| 12.10.2 | Sidac | 437 |
| 12.11 | Solved Examples | 438 |
| | Review Questions. | 439 |
| | Objective Questions | 440 |
| | Answers | 442 |

Part V Fabrication Techniques

| | | |
|-----------|---|------------|
| 13 | Semiconductor Growth Techniques and Device Fabrication | 445 |
| 13.1 | Introduction | 445 |
| 13.2 | Production of Element Form of Silicon (Si) | 446 |
| 13.3 | Semiconductor Bulk and Thin Films Growth Technologies | 446 |
| 13.4 | Semiconductor Crystal Growth | 448 |
| 13.4.1 | Bridgman Method | 448 |
| 13.4.2 | Czochralski Method. | 449 |
| 13.4.3 | Float Zone Method | 450 |
| 13.5 | Processing of Semiconducting Materials. | 451 |
| 13.5.1 | Zone Refining Process | 451 |
| 13.5.2 | Zone Refining Apparatus | 452 |
| 13.6 | Semiconductors Fabrication Technology. | 453 |
| 13.6.1 | Microelectronic Circuit Construction | 454 |
| 13.6.2 | Thin Film Circuit Fabrication | 454 |
| 13.7 | Manufacturing of Wafers | 455 |
| 13.8 | Ion-Implantation | 455 |
| 13.9 | Lithography | 456 |
| 13.9.1 | Photoresists | 457 |
| 13.9.2 | Photolithography | 457 |
| 13.10 | Epitaxy | 457 |
| 13.10.1 | Vapour Phase Epitaxy | 458 |
| 13.10.2 | Liquid Phase Epitaxy. | 459 |
| 13.10.3 | Molecular Beam Epitaxy (MBE). | 459 |

| | | |
|---------|---|-----|
| 13.11 | Chemical Vapour Deposition (CVD) | 460 |
| 13.12 | Sputtering | 460 |
| 13.13 | Masking | 461 |
| 13.14 | Etching | 462 |
| 13.15 | Metal Deposition Techniques | 462 |
| 13.16 | Fabrication Techniques of P–N Junction | 463 |
| 13.16.1 | Grown Junction Diode | 463 |
| 13.16.2 | Alloy Type (or Fused) Junction | 463 |
| 13.16.3 | Diffused Junction | 464 |
| 13.16.4 | Epitaxial Growth (or Planar Diffused) Junction | 466 |
| 13.16.5 | Point Contact Junction | 466 |
| 13.17 | Summary of the Fabrication of a Semiconductor P–N Junction | 467 |
| 13.18 | Transistor Manufacturing Processes | 467 |
| 13.19 | Solved Examples | 467 |
| | Review Questions | 470 |
| | Objective Questions | 472 |
| | Answers | 472 |
| | References | 473 |

Part VI Special Purpose and Nano-Structured Semiconductors, and Recent Advances

14 Special Semiconducting Materials in Vivid Fields

| | | |
|--------|---|------------|
| | (for Thermoelectrics, Integrated Circuits, Photocatalytics, Spintronic Devices, etc.), Plasmonic Solar Cell, and Photonics | 477 |
| 14.1 | Semiconductor Nanoparticles in Solar Cell Construction | 477 |
| 14.2 | Three-Dimensional (3D) Semiconductor Solar Cells | 478 |
| 14.3 | Semiconductor (ZnS) as Optical Material Applications | 478 |
| 14.4 | Scope of ZnS Nanoparticles Semiconductor | 479 |
| 14.5 | Semiconductors in Thermoelectric (TE) Applications | 480 |
| 14.6 | Semiconductors as High-ZT Thermoelectric Materials | 482 |
| 14.6.1 | Chalcogenides and Pentatellurides: The Complex Inorganic Structures | 482 |
| 14.6.2 | Skutterudites: The Crystal Structures with “Rattlers” | 482 |
| 14.6.3 | Oxide Thermoelectrics | 483 |
| 14.7 | Semiconducting Materials for Integrated Circuits | 483 |
| 14.7.1 | Silicon Carbide (SiC) for High Temperature ICs | 484 |
| 14.7.2 | Gallium Nitride (GaN) | 485 |
| 14.7.3 | Indium Phosphide (InP) | 485 |
| 14.7.4 | Silicon Germanium (SiGe) | 486 |

| | | |
|-----------|--|------------|
| 14.7.5 | Gallium Arsenide (GaAs) | 486 |
| 14.7.6 | Comparative Study of Different Semiconducting Materials for Integrated Circuits | 487 |
| 14.8 | Semiconductor Photocatalytic Materials | 487 |
| 14.8.1 | ZnO Semiconductor as Photocatalytic Material . . . | 488 |
| 14.8.2 | Cu ₂ O Semiconductor as Photocatalytic Material | 488 |
| 14.8.3 | Iron Oxides Semiconductor as Photocatalytic Material | 489 |
| 14.8.4 | Sulfides Semiconductor as Photocatalytic Material | 489 |
| 14.8.5 | Semiconductor Chalcogenide as Photocatalytic Material | 489 |
| 14.8.6 | Bismuth Oxyhalides Semiconductors as Photocatalytic Material | 490 |
| 14.9 | Transparent Thin Film Transistors | 490 |
| 14.9.1 | Advances in Transparent Oxide Semiconductor Based Transistors | 491 |
| 14.10 | Semiconductor Based Spintronic Devices | 491 |
| 14.10.1 | GaAs Spin—Charge Converter | 492 |
| 14.11 | Heusler Alloy Search for the New Spintronic Materials . . . | 493 |
| 14.11.1 | Spin Injection Materials | 494 |
| 14.11.2 | Spin Transport in Semiconductors and Their Nanostructures | 494 |
| 14.11.3 | Graphene, a Challenge to Semiconductors | 495 |
| 14.12 | Plasmonic Solar Cells | 495 |
| 14.12.1 | Nonlinear Plasmonic Antennas | 497 |
| 14.12.2 | Scope and Applications of Plasmonic Solar Cells | 497 |
| 14.13 | Photonic Materials | 498 |
| 14.13.1 | Need of Photonics Instead of Electronics | 499 |
| 14.14 | Possible Applications of Photonic Materials | 499 |
| 14.14.1 | Photonic Processor | 500 |
| 14.14.2 | Photonic Crystals | 500 |
| 14.14.3 | Photonic Integrated Circuits | 501 |
| 14.14.4 | The Future of Photonics | 501 |
| 14.15 | Where Photovoltaic Meets Microelectronics | 502 |
| 14.16 | Solved Examples | 503 |
| | Review Questions | 504 |
| | References | 506 |
| 15 | Nano-Structured Semiconducting Materials and Devices | 509 |
| 15.1 | Surface Science of Free Standing Semiconductor Nanowires | 509 |

| | | |
|---------|--|-----|
| 15.2 | Application of Semiconductor as Nanowires Sheathed Inside Nanotubes: Manipulation, Properties and Applications | 510 |
| 15.3 | Copper Phthalocyanine Nanocrystals Embedded into Polymer Host: Preparation and Structural Characterization | 510 |
| 15.4 | Electrical Nanogap Devices for Biosensing. | 511 |
| 15.5 | Nanoparticle-Based Plasmonic Organic Photovoltaic Devices | 511 |
| 15.6 | Nanoscale Semiconductor “X” on Substrate “Y”—Processes, Devices, and Applications | 512 |
| 15.6.1 | Introduction | 513 |
| 15.6.2 | Large-Scale Nanowire-Array XoY. | 514 |
| 15.6.3 | Artificial Electronic Skin | 514 |
| 15.7 | Recent Advances in Semiconductor Nanowire Heterostructures | 515 |
| 15.8 | Synthesis, Assembly and Applications of Semiconductor Nanomembranes | 517 |
| 15.9 | Inorganic Nanomembranes | 518 |
| 15.10 | III-V Compound Semiconductor Nanostructures on Silicon: Epitaxial Growth, Properties, and Applications in Light Emitting Diodes and Lasers | 519 |
| 15.11 | Nanostructured Tin Dioxide Materials for Gas Sensor Applications | 520 |
| 15.12 | Quantum Transport in Semiconductor Nanostructures | 520 |
| 15.13 | Photonic Switching Devices Based on Semiconductor Nanostructures | 521 |
| 15.14 | Zinc Oxide Nanostructures: Growth, Properties and Applications. | 522 |
| 15.15 | Recent Trends on Nanostructures Based Solar Energy Applications: A Review | 523 |
| 15.16 | Design, Fabrication, and Modification of Nanostructured Semiconductor Materials for Environmental and Energy Applications | 523 |
| 15.17 | Application of Semiconductor and Metal Nanostructures in Biology and Medicine | 525 |
| 15.18 | Semiconductor Nanocrystals. | 525 |
| 15.19 | Metal/Semiconductor Hybrid Nanostructures for Plasmon-Enhanced Applications. | 526 |
| 15.19.1 | Semiconductor Nanostructures. | 527 |
| 15.20 | Application of Nd:Yag Laser in Semiconductors’ Nanotechnology | 527 |
| 15.21 | Inorganic Semiconductor Nanostructures and Their Field-Emission Applications | 528 |

| | | |
|-----------|---|------------|
| 15.22 | Benchmarking Nanotechnology for High-Performance and Low-Power Logic Transistor Applications | 528 |
| 15.23 | Nanomaterials for Solar Energy Conversion | 529 |
| | References. | 529 |
| 16 | Recent Advances in Semiconducting Materials and Devices | 531 |
| 16.1 | Semiconductor Disk Lasers: Recent Advances in Generation of Yellow-Orange and Mid-IR Radiation | 531 |
| 16.1.1 | Introduction | 532 |
| 16.1.2 | Cavity Designs | 532 |
| 16.1.3 | Thermal Management of SDLs | 533 |
| 16.1.4 | Wavelength Coverage | 534 |
| 16.2 | High-Power Yellow-Orange SDLs Based on Dilute Nitride Gain Mirrors | 535 |
| 16.3 | GaSb-Based SDLs for 2–3 μm Wavelength Range | 538 |
| 16.3.1 | Continuous Wave GaSb Disk Laser. | 539 |
| 16.3.2 | Femtosecond Pulse Generation | 539 |
| 16.3.3 | Future Outlook | 539 |
| 16.4 | Recent Advances in Optically Pumped Semiconductor Lasers | 541 |
| 16.4.1 | Laser Diodes. | 541 |
| 16.5 | Optimization and Simplification of Polymerefullerene Solar Cells Through Polymer and Active Layer Design | 542 |
| 16.6 | Polymer Semiconductor Crystals. | 542 |
| 16.7 | Graphene for Radio Frequency Electronics. | 543 |
| 16.8 | Green and Biodegradable Electronics. | 544 |
| 16.9 | Modern Plastic Solar Cells: Materials, Mechanisms and Modeling. | 544 |
| 16.10 | Miniature Wire-Shaped Solar Cells, Electrochemical Capacitors and Lithium-Ion Batteries. | 545 |
| 16.10.1 | Miniature Inorganic Solar Cells. | 546 |
| 16.11 | Skin-Inspired Electronic Devices. | 547 |
| 16.12 | Recent Advances in Dye-Sensitized Solar Cells: From Photoanodes, Sensitizers and Electrolytes to Counter Electrodes | 548 |
| 16.13 | Investigation of the Optical Absorption of a-Si:H Solar Cells on Micro-and Nano-Textured Surfaces | 549 |
| 16.14 | POSFET Tactile Sensing Arrays Using CMOS Technology | 549 |
| 16.14.1 | Working Principle of a POSFET Touch Sensing Device | 550 |
| 16.15 | Oxide Semiconductor Thin-Film Transistors: A Review. | 550 |
| 16.15.1 | Amorphous Oxide Semiconductor | 551 |

| | | |
|---------|---|------------|
| 16.16 | Wide Band Gap Semiconductor Devices for Power Electronics | 551 |
| 16.16.1 | Introduction | 552 |
| 16.17 | SiC Power Devices | 553 |
| 16.18 | GaN Power Devices | 555 |
| 16.18.1 | GaN HEMT | 556 |
| 16.18.2 | New Generation of Power Devices | 557 |
| 16.19 | Heterogeneous Photocatalysis: Recent Advances and Applications | 558 |
| 16.20 | New Semiconductor Materials for Magnetoelectronics at Room Temperature | 558 |
| 16.20.1 | Materials and Methods | 559 |
| 16.20.2 | Alloy of II–VI Semiconductors with Magnetic Materials | 560 |
| 16.20.3 | Alloys of III–V Semiconductors with Ferromagnetic Properties | 560 |
| 16.21 | Tunable Left-Handed Metamaterial Based on Electro-Rheological Fluids | 561 |
| 16.21.1 | The Left-Handed Dendritic Model | 561 |
| | References | 562 |
| | Appendix | 563 |
| | Glossary | 565 |
| | References | 573 |

Advanced Semiconducting Materials and Devices

Gupta, K.M.; Gupta, N.

2016, XLII, 573 p., Hardcover

ISBN: 978-3-319-19757-9