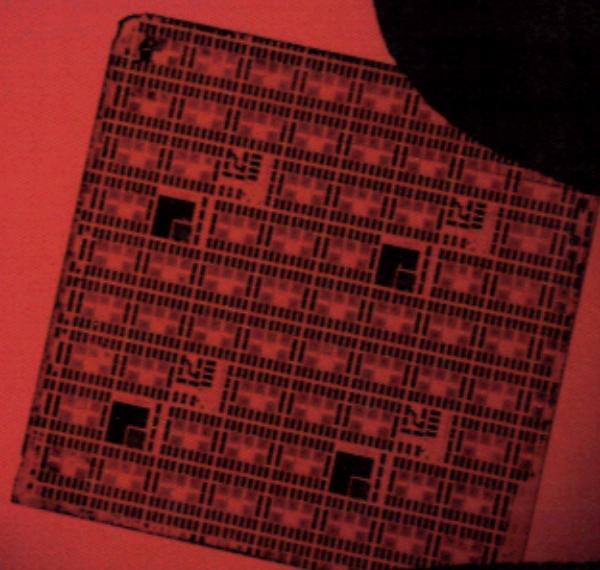


an introduction to
semiconductor devices



donald neamen

MCGRAW-HILL INTERNATIONAL EDITION



CONTENTS

Preface xvii

CHAPTER 1

The Crystal Structure of Solids 1

1.0 Preview 1

1.1 Semiconductor Materials 2

1.2 Types of Solids 3

1.3 Space Lattices 4

 1.3.1 Primitive and Unit Cell 4

 1.3.2 Basic Crystal Structures 6

 1.3.3 Crystal Planes and Miller Indices 7

 1.3.4 The Diamond Structure 13

1.4 Atomic Bonding 15

1.5 Imperfections and Impurities in Solids 17

 1.5.1 Imperfections in Solids 17

 1.5.2 Impurities in Solids 18

Σ 1.6 Growth of Semiconductor Materials 19

 1.6.1 Growth from a Melt 20

 1.6.2 Epitaxial Growth 22

Σ 1.7 Device Fabrication Techniques:

 Oxidation 23

1.8 Summary 25

Problems 27

CHAPTER 2

Theory of Solids 31

2.0 Preview 31

2.1 Principles of Quantum Mechanics 32

 2.1.1 Energy Quanta 32

 2.1.2 Wave-Particle Duality Principle 34

2.2 Energy Quantization and Probability Concepts 36

 2.2.1 Physical Meaning of the Wave Function 36

2.2.2 The One-Electron Atom 37

2.2.3 Periodic Table 40

2.3 Energy-Band Theory 41

 2.3.1 Formation of Energy Bands 41

 2.3.2 The Energy Band and the Bond Model 45

 2.3.3 Charge Carriers—Electrons and Holes 47

 2.3.4 Effective Mass 49

 2.3.5 Metals, Insulators, and Semiconductors 50

 2.3.6 The k -Space Diagram 52

2.4 Density of States Function 55

2.5 Statistical Mechanics 57

 2.5.1 Statistical Laws 57

 2.5.2 The Fermi-Dirac Distribution Function and the Fermi Energy 58

 2.5.3 Maxwell-Boltzmann Approximation 62

2.6 Summary 64

Problems 65

CHAPTER 3

The Semiconductor in Equilibrium 70

3.0 Preview 70

3.1 Charge Carriers in Semiconductors 71

 3.1.1 Equilibrium Distribution of Electrons and Holes 72

 3.1.2 The n_0 and p_0 Equations 74

 3.1.3 The Intrinsic Carrier Concentration 79

 3.1.4 The Intrinsic Fermi-Level Position 82

3.2 Dopant Atoms and Energy Levels 83

 3.2.1 Qualitative Description 83

 3.2.2 Ionization Energy 86

 3.2.3 Group III-V Semiconductors 88

3.3 Carrier Distributions in the Extrinsic Semiconductor 89

 3.3.1 Equilibrium Distribution of Electrons and Holes 89

<p>3.3.2 <i>The $n_0 p_0$ Product</i> 93</p> <p>Σ 3.3.3 <i>The Fermi–Dirac Integral</i> 94</p> <p>3.3.4 <i>Degenerate and Nondegenerate Semiconductors</i> 96</p> <p>3.4 Statistics of Donors and Acceptors 97</p> <p>3.4.1 <i>Probability Function</i> 98</p> <p>Σ 3.4.2 <i>Complete Ionization and Freeze-Out</i> 99</p> <p>3.5 Carrier Concentrations—Effects of Doping 102</p> <p>3.5.1 <i>Compensated Semiconductors</i> 102</p> <p>3.5.2 <i>Equilibrium Electron and Hole Concentrations</i> 102</p> <p>3.6 Position of Fermi Energy Level—Effects of Doping and Temperature 109</p> <p>3.6.1 <i>Mathematical Derivation</i> 109</p> <p>3.6.2 <i>Variation of E_F with Doping Concentration and Temperature</i> 112</p> <p>3.6.3 <i>Relevance of the Fermi Energy</i> 114</p> <p>Σ 3.7 Device Fabrication Technology: Diffusion and Ion Implantation 115</p> <p>3.7.1 <i>Impurity Atom Diffusion</i> 116</p> <p>3.7.2 <i>Impurity Atom Ion Implantation</i> 118</p> <p>3.8 Summary 119</p> <p>Problems 121</p>	<p>4.4 Carrier Generation and Recombination 153</p> <p>4.4.1 <i>The Semiconductor in Equilibrium</i> 154</p> <p>4.4.2 <i>Excess Carrier Generation and Recombination</i> 155</p> <p>4.4.3 <i>Generation–Recombination Processes</i> 158</p> <p>Σ 4.5 The Hall Effect 161</p> <p>4.6 Summary 164</p> <p>Problems 166</p>
--	--

CHAPTER 4

Carrier Transport and Excess Carrier Phenomena 128

<p>4.0 Preview 128</p> <p>4.1 Carrier Drift 129</p> <p>4.1.1 <i>Drift Current Density</i> 129</p> <p>4.1.2 <i>Mobility Effects</i> 132</p> <p>4.1.3 <i>Semiconductor Conductivity and Resistivity</i> 137</p> <p>4.1.4 <i>Velocity Saturation</i> 143</p> <p>4.2 Carrier Diffusion 145</p> <p>4.2.1 <i>Diffusion Current Density</i> 145</p> <p>4.2.2 <i>Total Current Density</i> 148</p> <p>4.3 Graded Impurity Distribution 149</p> <p>4.3.1 <i>Induced Electric Field</i> 149</p> <p>4.3.2 <i>The Einstein Relation</i> 152</p>	<p>5.0 Preview 174</p> <p>5.1 Basic Structure of the pn Junction 175</p> <p>5.2 The pn Junction—Zero Applied Bias 176</p> <p>5.2.1 <i>Built-In Potential Barrier</i> 177</p> <p>5.2.2 <i>Electric Field</i> 179</p> <p>5.2.3 <i>Space Charge Width</i> 183</p> <p>5.3 The pn Junction—Reverse Applied Bias 185</p> <p>5.3.1 <i>Space Charge Width and Electric Field</i> 186</p> <p>5.3.2 <i>Junction Capacitance</i> 189</p> <p>5.3.3 <i>One-Sided Junctions</i> 192</p> <p>5.4 Metal–Semiconductor Contact—Rectifying Junction 194</p> <p>5.4.1 <i>The Schottky Barrier</i> 194</p> <p>5.4.2 <i>The Schottky Junction—Reverse Bias</i> 196</p> <p>5.5 Forward Applied Bias—An Introduction 197</p> <p>5.5.1 <i>The pn Junction</i> 197</p> <p>5.5.2 <i>The Schottky Barrier Junction</i> 199</p> <p>5.5.3 <i>Comparison of the Schottky Diode and the pn Junction Diode</i> 201</p> <p>Σ 5.6 Metal–Semiconductor Ohmic Contacts 203</p> <p>Σ 5.7 Nonuniformly Doped pn Junctions 206</p> <p>5.7.1 <i>Linearly Graded Junctions</i> 206</p> <p>5.7.2 <i>Hyperabrupt Junctions</i> 208</p> <p>Σ 5.8 Device Fabrication Techniques: Photolithography, Etching, and Bonding 210</p>
---	--

<p>5.8.1 <i>Photomasks and Photolithography</i> 210</p> <p>5.8.2 <i>Etching</i> 211</p> <p>5.8.3 <i>Impurity Diffusion or Ion Implantation</i> 211</p> <p>5.8.4 <i>Metallization, Bonding, and Packaging</i> 211</p> <p>5.9 Summary 212</p> <p>Problems 215</p>	<p>6.6 Small-Signal Equivalent Circuit and Frequency Limitation Factors 290</p> <p>6.6.1 <i>Transconductance</i> 290</p> <p>6.6.2 <i>Small-Signal Equivalent Circuit</i> 291</p> <p>6.6.3 <i>Frequency Limitation Factors and Cutoff Frequency</i> 293</p> <p>Σ 6.7 Device Fabrication Techniques 296</p> <p>6.7.1 <i>Fabrication of an NMOS Transistor</i> 296</p> <p>6.7.2 <i>The CMOS Technology</i> 297</p> <p>6.8 Summary 299</p> <p>Problems 301</p>
CHAPTER 6 Fundamentals of the Metal–Oxide–Semiconductor Field-Effect Transistor 223	
<p>6.0 Preview 223</p> <p>6.1 The MOS Field-Effect Transistor Action 224</p> <p>6.1.1 <i>Basic Principle of Operation</i> 225</p> <p>6.1.2 <i>Modes of Operation</i> 226</p> <p>6.1.3 <i>Amplification with MOSFETs</i> 226</p> <p>6.2 The Two-Terminal MOS Capacitor 227</p> <p>6.2.1 <i>Energy-Band Diagrams and Charge Distributions</i> 228</p> <p>6.2.2 <i>Depletion Layer Thickness</i> 235</p> <p>6.3 Potential Differences in the MOS Capacitor 239</p> <p>6.3.1 <i>Work Function Differences</i> 240</p> <p>6.3.2 <i>Oxide Charges</i> 244</p> <p>6.3.3 <i>Flat-Band Voltage</i> 245</p> <p>6.3.4 <i>Threshold Voltage</i> 247</p> <p>Σ 6.3.5 <i>Electric Field Profile</i> 254</p> <p>6.4 Capacitance–Voltage Characteristics 258</p> <p>6.4.1 <i>Ideal C–V Characteristics</i> 258</p> <p>Σ 6.4.2 <i>Frequency Effects</i> 263</p> <p>Σ 6.4.3 <i>Fixed Oxide and Interface Charge Effects</i> 264</p> <p>6.5 The Basic MOSFET Operation 268</p> <p>6.5.1 <i>MOSFET Structures</i> 268</p> <p>6.5.2 <i>Current–Voltage Relationship—Basic Concepts</i> 270</p> <p>Σ 6.5.3 <i>Current–Voltage Relationship—Mathematical Derivation</i> 282</p> <p>6.5.4 <i>Substrate Bias Effects</i> 287</p>	<p>CHAPTER 7 Metal–Oxide–Semiconductor Field-Effect Transistor: Additional Concepts 311</p> <p>7.0 Preview 311</p> <p>7.1 MOSFET Scaling 312</p> <p>7.1.1 <i>Constant-Field Scaling</i> 312</p> <p>7.1.2 <i>Threshold Voltage—First Approximation</i> 313</p> <p>7.1.3 <i>Generalized Scaling</i> 314</p> <p>7.2 Nonideal Effects 315</p> <p>7.2.1 <i>Subthreshold Conduction</i> 315</p> <p>7.2.2 <i>Channel Length Modulation</i> 318</p> <p>7.2.3 <i>Mobility Variation</i> 321</p> <p>7.2.4 <i>Velocity Saturation</i> 324</p> <p>7.3 Threshold Voltage Modifications 326</p> <p>7.3.1 <i>Short-Channel Effects</i> 327</p> <p>7.3.2 <i>Narrow-Channel Effects</i> 331</p> <p>7.3.3 <i>Substrate Bias Effects</i> 333</p> <p>7.4 Additional Electrical Characteristics 335</p> <p>7.4.1 <i>Oxide Breakdown</i> 335</p> <p>7.4.2 <i>Near Punch-Through or Drain-Induced Barrier Lowering</i> 335</p> <p>7.4.3 <i>Hot Electron Effects</i> 337</p> <p>7.4.4 <i>Threshold Adjustment by Ion Implantation</i> 338</p> <p>7.5 Device Fabrication Techniques: Specialized Devices 341</p> <p>7.5.1 <i>Lightly Doped Drain Transistor</i> 342</p> <p>7.5.2 <i>The MOSFET on Insulator</i> 343</p>

7.5.3	<i>The Power MOSFET</i>	345	9.1.1	<i>The pn Junction</i>	399
7.5.4	<i>MOS Memory Device</i>	348	9.1.2	<i>The Schottky Barrier Junction</i>	402
7.6	Summary	350	9.2	The pn Junction—Ideal Current–Voltage Relationship	404
	Problems	352	9.2.1	<i>Boundary Conditions</i>	404
C H A P T E R 8					
Nonequilibrium Excess Carriers in Semiconductors 358					
8.0	Preview	358	9.2.2	<i>Minority-Carrier Distribution</i>	409
8.1	Carrier Generation and Recombination	359	9.2.3	<i>Ideal pn Junction Current</i>	411
8.2	Analysis of Excess Carriers	360	9.2.4	<i>Summary of Physics</i>	416
	8.2.1 <i>Continuity Equations</i>	361	9.2.5	<i>Temperature Effects</i>	418
	8.2.2 <i>Time-Dependent Diffusion Equations</i>	362	9.2.6	<i>The “Short” Diode</i>	420
8.3	Ambipolar Transport	364	9.2.7	<i>Summary of Results</i>	422
	8.3.1 <i>Derivation of the Ambipolar Transport Equation</i>	364	9.3	The Schottky Barrier Junction—Ideal Current–Voltage Relationship	423
	8.3.2 <i>Limits of Extrinsic Doping and Low Injection</i>	366	9.3.1	<i>The Schottky Diode</i>	423
	8.3.3 <i>Applications of the Ambipolar Transport Equation</i>	368	9.3.2	<i>Comparison of the Schottky Diode and the pn Junction Diode</i>	426
	8.3.4 <i>Dielectric Relaxation Time Constant</i>	376	9.4	Small-Signal Model of the pn Junction	428
	8.3.5 <i>Haynes–Shockley Experiment</i>	379	9.4.1	<i>Diffusion Resistance</i>	428
8.4	Quasi-Fermi Energy Levels	382	9.4.2	<i>Small-Signal Admittance</i>	430
8.5	Excess Carrier Lifetime	385	9.4.3	<i>Equivalent Circuit</i>	432
	8.5.1 <i>Shockley–Read–Hall Theory of Recombination</i>	385	9.5	Generation–Recombination Currents	434
	8.5.2 <i>Limits of Extrinsic Doping and Low Injection</i>	387	9.5.1	<i>Reverse-Bias Generation Current</i>	434
8.6	Surface Effects	389	9.5.2	<i>Forward-Bias Recombination Current</i>	437
	8.6.1 <i>Surface States</i>	389	9.5.3	<i>Total Forward-Bias Current</i>	439
	8.6.2 <i>Surface Recombination Velocity</i>	390	9.6	Junction Breakdown	441
8.7	Summary	391	9.7	Charge Storage and Diode Transients	446
	Problems	392	9.7.1	<i>The Turn-Off Transient</i>	446
C H A P T E R 9					
The pn Junction and Schottky Diodes 398					
9.0	Preview	398	9.7.2	<i>The Turn-On Transient</i>	449
9.1	The pn and Schottky Barrier Junctions Revisited	399	9.8	Summary	449
	Problems	392		Problems	451
C H A P T E R 10					
The Bipolar Transistor 460					
10.0	Preview	460			
10.1	The Bipolar Transistor Action	461	10.1.1	<i>The Basic Principle of Operation</i>	462
	10.1.2 <i>Simplified Transistor Current Relations</i>	466	10.1.3	<i>The Modes of Operation</i>	468
	10.1.4 <i>Amplification with Bipolar Transistors</i>	470			

10.2	Minority-Carrier Distribution 472	11.2	Heterojunctions 560
10.2.1	<i>Forward-Active Mode</i> 472	11.2.1	<i>The Heterojunction</i> 560
10.2.2	<i>Other Modes of Operation</i> 480	11.2.2	<i>Heterojunction Bipolar Transistors</i> 564
10.3	Low-frequency Common-Base Current Gain 483	11.2.3	<i>High-Electron Mobility Transistor</i> 566
10.3.1	<i>Contributing Factors</i> 483	11.3	The Thyristor 567
10.3.2	<i>Mathematical Derivation of Current Gain Factors</i> 486	11.3.1	<i>The Basic Characteristics</i> 568
10.3.3	<i>Summary and Review</i> 489	11.3.2	<i>Triggering the SCR</i> 570
10.3.4	<i>Example Calculations of the Gain Factors</i> 490	11.3.3	<i>Device Structures</i> 574
10.4	Nonideal Effects 495	11.4	Additional MOSFET Concepts 578
10.4.1	<i>Base Width Modulation</i> 495	11.4.1	<i>Latch-Up</i> 578
10.4.2	<i>High Injection</i> 499	11.4.2	<i>Breakdown</i> 580
10.4.3	<i>Emitter Bandgap Narrowing</i> 501	11.5	Microelectromechanical Systems (MEMS) 583
10.4.4	<i>Current Crowding</i> 503	11.5.1	<i>Accelerometers</i> 583
Σ 10.4.5	<i>Nonuniform Base Doping</i> 506	11.5.2	<i>Inkjet Printing</i> 584
10.4.6	<i>Breakdown Voltage</i> 507	11.5.3	<i>Biomedical Sensors</i> 584
10.5	Hybrid-Pi Equivalent Circuit Model 513	11.6	Summary 586
10.6	Frequency Limitations 517	Problems 587	
10.6.1	<i>Time-Delay Factors</i> 517		
10.6.2	<i>Transistor Cutoff Frequency</i> 519		
Σ 10.7	Large-Signal Switching 522		
Σ 10.8	Device Fabrication Techniques 524		
10.8.1	<i>Polysilicon Emitter BJT</i> 524	12.0	Preview 590
10.8.2	<i>Fabrication of Double-Polysilicon npn Transistor</i> 525	12.1	Optical Absorption 591
10.8.3	<i>Silicon-Germanium Base Transistor</i> 527	12.1.1	<i>Photon Absorption Coefficient</i> 591
10.8.4	<i>The Power BJT</i> 529	12.1.2	<i>Electron–Hole Pair Generation Rate</i> 594
10.9	Summary 533	12.2	Solar Cells 596
Problems 535		12.2.1	<i>The pn Junction Solar Cell</i> 596
		12.2.2	<i>Conversion Efficiency and Solar Concentration</i> 599
		12.2.3	<i>The Heterojunction Solar Cell</i> 601
		12.2.4	<i>Amorphous Silicon Solar Cells</i> 603
CHAPTER 11			
Additional Semiconductor Devices and Device Concepts 546			
11.0	Preview 546	12.3	Photodetectors 605
11.1	The Junction Field-Effect Transistor 547	12.3.1	<i>Photoconductor</i> 605
11.1.1	<i>The pn JFET</i> 547	12.3.2	<i>Photodiode</i> 608
11.1.2	<i>The MESFET</i> 551	12.3.3	<i>PIN Photodiode</i> 611
11.1.3	<i>Electrical Characteristics</i> 553	12.3.4	<i>Avalanche Photodiode</i> 614
		12.3.5	<i>Phototransistor</i> 614
		12.4	Light-Emitting Diodes 616
		12.4.1	<i>Generation of Light</i> 616

CHAPTER 12

Optical Devices 590

12.0	Preview 590
12.1	Optical Absorption 591
12.1.1	<i>Photon Absorption Coefficient</i> 591
12.1.2	<i>Electron–Hole Pair Generation Rate</i> 594
12.2	Solar Cells 596
12.2.1	<i>The pn Junction Solar Cell</i> 596
12.2.2	<i>Conversion Efficiency and Solar Concentration</i> 599
12.2.3	<i>The Heterojunction Solar Cell</i> 601
12.2.4	<i>Amorphous Silicon Solar Cells</i> 603
12.3	Photodetectors 605
12.3.1	<i>Photoconductor</i> 605
12.3.2	<i>Photodiode</i> 608
12.3.3	<i>PIN Photodiode</i> 611
12.3.4	<i>Avalanche Photodiode</i> 614
12.3.5	<i>Phototransistor</i> 614
12.4	Light-Emitting Diodes 616
12.4.1	<i>Generation of Light</i> 616

12.4.2	<i>Internal Quantum Efficiency</i>	616
12.4.3	<i>External Quantum Efficiency</i>	618
12.4.4	<i>LED Devices</i>	620
12.5	Laser Diodes	622
12.5.1	<i>Stimulated Emission and Population Inversion</i>	622
12.5.2	<i>Optical Cavity</i>	625
12.5.3	<i>Threshold Current</i>	627
12.5.4	<i>Device Structures and Characteristics</i>	627
12.6	Summary	629
	Problems	631

APPENDIX A	
Selected List of Symbols	636

APPENDIX B	
System of Units, Conversion Factors, and General Constants	643

APPENDIX C	
The Periodic Table	647

APPENDIX D	
Unit of Energy—The Electron-Volt	648

APPENDIX E	
“Derivation” and Applications of Schrödinger’s Wave Equation	650

APPENDIX F	
Answers to Selected Problems	656
Index	663