

Contents

Preface	VII
1 Introduction to Semiconductor Physics	1
1.1 Insulators, Conductors and Semiconductors	1
<i>Insulators</i>	1
<i>Conductors</i>	2
<i>Semiconductors</i>	2
1.2 Semiconductor Types	4
<i>Intrinsic Semiconductors</i>	4
<i>N-Type Extrinsic Semiconductors</i>	10
<i>P-Type Extrinsic Semiconductors</i>	14
1.3 Law of Mass Action	18
1.4 Drift and Diffusion Carriers	20
1.5 Hall Effect	21
Key Terms	22
Objective-Type Exercises	22
Review Questions	23
Problems	24
Answers	24
2 Semiconductor Diodes	25
2.1 P-N Junction	25
<i>Forward-Bias Condition</i>	27
<i>Reverse-Bias Condition</i>	27
2.2 Ideal Diode	28
2.3 Practical Diode	29
2.4 V-I Characteristics of a Diode	29
2.5 Temperature Dependence of the V-I Characteristics	30
2.6 Diode Specifications	31
2.7 Diode Resistance	33
<i>Static Resistance</i>	34
<i>Dynamic Resistance</i>	35
<i>Average AC Resistance</i>	36
2.8 Diode Junction Capacitance	37
<i>Transition Capacitance</i>	38
<i>Diffusion Capacitance</i>	38
2.9 Diode Equivalent Circuits	38
2.10 Load-Line Analysis of a Diode Circuit	43
<i>DC Applied Voltage</i>	43
<i>AC Applied Voltage</i>	44
2.11 Breakdown Diodes	48
<i>Avalanche Diodes</i>	49
<i>Zener Diodes</i>	49
2.12 Varactor Diodes	50
2.13 Tunnel Diodes	51

xii Contents

2.14	Schottky Diodes	53
2.15	Point-Contact Diodes and Power Diodes	54
	<i>Point-Contact Diodes</i>	54
	<i>Power Diodes</i>	54
2.16	Light-Emitting Diodes	54
2.17	Photodiodes	56
2.18	Connecting Diodes in Series and in Parallel	56
	<i>Diodes in Series</i>	56
	<i>Diodes in Parallel</i>	57
2.19	Diode Numbers and Lead Identification	58
2.20	Diode Testing	59
	Key Terms	60
	Objective-Type Exercises	61
	Review Questions	62
	Problems	63
	Answers	65
3	Bipolar Junction Transistors	69
3.1	Bipolar Junction Transistor versus Vacuum Triode	70
3.2	Transistor Construction and Types	70
	<i>NPN Transistor</i>	70
	<i>PNP Transistor</i>	70
3.3	Transistor Operation	71
3.4	Common-Base Configuration	73
	<i>Input Characteristics</i>	73
	<i>Output Characteristics</i>	75
3.5	Common-Emitter Configuration	78
	<i>Input Characteristics</i>	78
	<i>Output Characteristics</i>	79
3.6	Common-Collector Configuration	83
	<i>Input Characteristics</i>	83
	<i>Output Characteristics</i>	83
3.7	Ebers–Moll Model of Transistors	86
3.8	Transistor Specifications and Maximum Ratings	87
3.9	Lead Identification	89
3.10	Transistor Testing	92
3.11	Phototransistors	94
3.12	Power Transistors	94
3.13	Transistor Construction Techniques	96
	<i>Point-Contact Transistors</i>	96
	<i>Grown-Junction Type Transistors</i>	96
	<i>Alloy-Junction Transistors</i>	97
	<i>Diffusion Transistors</i>	97
	<i>Epitaxial Transistors</i>	98
	<i>Annular Transistors</i>	98
	Key Terms	98

Objective-Type Exercises	98
Review Questions	101
Problems	101
Answers	102
4 Transistor Biasing and Thermal Stabilization	103
4.1 Operating Point	103
4.2 Common-Emitter Configuration	105
<i>Fixed-Bias Circuit</i>	105
<i>Emitter-Bias or Self-Bias Configuration</i>	110
<i>Voltage-Divider-Bias with Emitter-Bias Configuration</i>	115
<i>Collector-to-Base-Bias Configuration</i>	124
4.3 Common-Base Circuit	128
4.4 Common-Collector Circuit	130
4.5 Bias Stabilization	132
<i>Stability Factor</i>	133
<i>Stability Factor ($S_{I_{CO}}$)</i>	134
<i>Stability Factor ($S_{V_{BE}}$)</i>	136
<i>Stability Factor (S_{β})</i>	138
4.6 Bias Compensation	144
<i>Diode Compensation for Base-Emitter Voltage (V_{BE})</i>	144
<i>Diode Compensation for Leakage Current (I_{CO})</i>	145
<i>Thermistor Compensation</i>	146
4.7 Thermal Runaway	146
<i>Operating-Point Considerations in Thermal Runaway</i>	148
4.8 Transistor Switch	152
<i>Transistor Switching Delays</i>	153
Key Terms	157
Objective-Type Exercises	157
Review Questions	158
Problems	159
Answers	161
5 Field Effect Transistors	165
5.1 Bipolar Junction Transistors versus Field Effect Transistors	165
5.2 Junction Field Effect Transistors	166
<i>Construction and Principle of Operation</i>	166
<i>Characteristic Curves</i>	167
<i>Effect of Temperature on JFET Parameters</i>	170
5.3 Metal Oxide Field Effect Transistors	171
<i>Depletion MOSFETs</i>	171
<i>Enhancement MOSFETs</i>	173
5.4 FET Parameters and Specifications	178
<i>Characteristic Parameters</i>	178
<i>FET Datasheet Specifications</i>	180
5.5 Differences between JFETs and MOSFETs	182
5.6 Handling MOSFETs	182

xiv Contents

5.7	Biasing JFETs	183
	<i>Common-Source Configuration</i>	183
	<i>Common-Drain Configuration</i>	190
	<i>Common-Gate Configuration</i>	192
5.8	Biasing MOSFETs	192
	<i>Depletion MOSFETs</i>	192
	<i>Enhancement MOSFETs</i>	194
5.9	FET Applications	200
5.10	Testing FETs	203
5.11	Dual-Gate MOSFET	204
5.12	VMOS Devices	205
5.13	CMOS Devices	206
5.14	Insulated Gate Bipolar Transistors (IGBTs)	207
	Key Terms	209
	Objective-Type Exercises	210
	Review Questions	212
	Problems	213
	Answers	214
6	UJTs and Thyristors	215
6.1	Unijunction Transistor	215
	<i>Construction</i>	216
	<i>Operational Principle</i>	217
	<i>Current-Controllable Device</i>	218
	<i>UJT Relaxation Oscillator Circuit</i>	218
6.2	PNPN Diode	220
	<i>PNPN Diode Material</i>	222
	<i>PNPN Diode Characteristics</i>	222
	<i>PNPN Diode as Relaxation Oscillator</i>	224
	<i>Rate Effect</i>	226
6.3	Silicon-Controlled Rectifier	227
	<i>V-I Characteristics</i>	228
	<i>Gate-Triggering Characteristics</i>	228
6.4	DIAC and TRIAC	229
6.5	Thyristor Parameters	230
	<i>Repetitive Peak Reverse Voltage</i>	231
	<i>Non-Repetitive Peak Reverse Voltage</i>	231
	<i>Repetitive Peak OFF-State Voltage</i>	232
	<i>Break-Over Voltage</i>	232
	<i>Critical Rate of Rise of ON-State Current</i>	232
	<i>Critical Rate of Rise of OFF-State Voltage</i>	232
	<i>Holding Current and Holding Voltage</i>	232
	<i>Latching Current</i>	233
	<i>Amperes Squared Seconds (I^2t) Rating</i>	233
6.6	Thyristors as Current-Controllable Devices	233
6.7	Thyristors in Series	234

6.8	Thyristors in Parallel	234
6.9	Applications of Thyristors	235
	<i>SCR as Pulse Generator</i>	235
	<i>SCR as Bistable Multivibrator</i>	236
	<i>Half-Wave Controlled Rectifier</i>	236
	<i>Full-Wave Controlled Rectifier</i>	236
	<i>TRIAC-Based AC Power Control</i>	238
	<i>SCR-Based Crowbar Protection</i>	238
6.10	Gate Turn-OFF Thyristors	241
6.11	Programmable Unijunction Transistor	241
	Key Terms	243
	Objective-Type Exercises	243
	Review Questions	246
	Problems	246
	Answers	248
7	Optoelectronic Devices	249
7.1	Optoelectronic Devices	250
	<i>Classification</i>	250
	<i>Radiometric and Photometric Units</i>	250
7.2	Photosensors	252
	<i>Characteristic Parameters</i>	252
7.3	Photoconductors	255
	<i>Application Circuits</i>	255
7.4	Photodiodes	259
	<i>Photodiode Types</i>	259
	<i>V-I Characteristics of a Photodiode</i>	262
	<i>Photodiode Application Circuits</i>	263
	<i>Solar Cells</i>	264
7.5	Phototransistors	268
	<i>Phototransistor Application Circuits</i>	269
7.6	PhotoFET, PhotoSCR and PhotoTRIAC	270
	<i>PhotoFET</i>	271
	<i>PhotoSCR</i>	271
	<i>PhotoTRIAC</i>	272
7.7	Photoemissive Sensors	273
	<i>Vacuum Photodiodes</i>	273
	<i>Photomultiplier Tubes</i>	273
	<i>Image Intensifiers</i>	274
7.8	Thermal Sensors	275
	<i>Thermocouple and Thermopile</i>	275
	<i>Bolometers</i>	276
	<i>Pyroelectric Sensors</i>	276
7.9	Displays	278
	<i>Display Characteristics</i>	278
	<i>Types of Displays</i>	278

xvi Contents

7.10	Light-Emitting Diodes	279
	<i>LED Characteristic Curves</i>	280
	<i>LED Parameters</i>	280
	<i>LED Drive Circuits</i>	281
7.11	Liquid Crystal Displays	284
	<i>Construction of an LCD</i>	284
	<i>Driving an LCD</i>	285
	<i>LCD Response Time</i>	287
	<i>Liquid Crystal Display Types</i>	287
	<i>Advantages and Disadvantages</i>	288
7.12	Cathode Ray Tube Displays	288
	<i>Advantages and Disadvantages</i>	289
7.13	Emerging Display Technologies	289
	<i>Organic Light-Emitting Diodes (OLEDs)</i>	290
	<i>Digital Light Processing (DLP) Technology</i>	290
	<i>Plasma Display Panels (PDP)</i>	290
	<i>Field Emission Displays (FEDs)</i>	290
	<i>Electronic Ink Displays</i>	290
7.14	Optocouplers	291
	<i>Optocoupler Parameters</i>	291
	<i>Optocoupler Application Circuits</i>	293
	Key Terms	297
	Objective-Type Exercises	298
	Review Questions	299
	Problems	300
	Answers	301
8	Small Signal Analysis of Amplifiers	303
8.1	Amplifier Bandwidth: General Frequency Considerations	303
8.2	Hybrid h-Parameter Model for an Amplifier	305
	<i>Determination of h-Parameters</i>	306
8.3	Transistor Hybrid Model	307
	<i>h-Parameter Model for the Common-Emitter Configuration</i>	307
	<i>Relationships between h-Parameters of Different Transistor Configurations</i>	309
	<i>Graphical Determination of h-Parameters</i>	312
8.4	Analysis of a Transistor Amplifier using Complete h-Parameter Model	314
8.5	Analysis of Transistor Amplifier Configurations using Simplified h-Parameter Model	320
	<i>Common-Emitter Configuration</i>	320
	<i>Emitter-Follower Configuration</i>	323
	<i>Common-Base Configuration</i>	325
8.6	Small-Signal Analysis of FET Amplifiers	328
	<i>Common-Source FET Amplifier</i>	329
	<i>Common-Drain FET Amplifier</i>	330
8.7	Cascading Amplifiers	333
	<i>BJT Cascade Amplifier</i>	334
	<i>FET Cascade Amplifier</i>	337

8.8	Darlington Amplifiers	338
8.9	Cascode Amplifiers	343
8.10	Low-Frequency Response of Amplifiers	344
	<i>Low-Frequency Response of BJT Amplifiers</i>	345
	<i>Low-Frequency Response of FET Amplifiers</i>	347
8.11	Low-Frequency Response of Cascaded Amplifier Stages	350
	Key Terms	351
	Objective-Type Exercises	351
	Review Questions	353
	Problems	353
	Answers	355
9	High-Frequency Response of Small-Signal Amplifiers	357
9.1	High-Frequency Model for the Common-Emitter Transistor Amplifier	357
	<i>Hybrid-Π Conductances</i>	358
	<i>Hybrid-Π Capacitances</i>	361
	<i>Variation of Hybrid-Π Parameters</i>	361
9.2	Common-Emitter Short-Circuit Current Gain	362
	β Cut-Off Frequency	363
	<i>Gain-Bandwidth Product</i>	364
	α Cut-Off Frequency	364
9.3	Miller's Theorem	366
9.4	Common-Emitter Current Gain with Resistive Load	370
9.5	High-Frequency Response of Common-Collector Transistor Amplifier	371
9.6	High-Frequency Response of an FET Amplifier	374
	<i>Common-Source Amplifier at High Frequencies</i>	374
	<i>Common-Drain Amplifier at High Frequencies</i>	377
9.7	High-Frequency Response of Cascaded Amplifier Stages	378
9.8	Amplifier Rise Time and Sag	381
	<i>Rise Time</i>	381
	<i>Tilt or Sag</i>	381
	Key Terms	382
	Objective-Type Exercises	382
	Review Questions	383
	Problems	384
	Answers	384
10	Large Signal Amplifiers	385
10.1	Large Signal Amplifiers	386
	<i>Classification</i>	386
	<i>Large Signal Amplifier Characteristics</i>	389
10.2	Class A Amplifiers	393
	<i>Class A Amplifier with Direct-Coupled Resistive Load</i>	393
	<i>Transformer-Coupled Class A Amplifiers</i>	397
	<i>Class A Push-Pull Amplifiers</i>	403

10.3	Class B Amplifiers	405
	<i>Transformer-Coupled Push–Pull Class B Amplifier</i>	406
	<i>Complementary-Symmetry Push–Pull Class B Amplifier</i>	410
	<i>Quasi-Complementary Push–Pull Class B Amplifier</i>	410
10.4	Class AB Amplifiers	413
10.5	Class C Amplifiers	413
10.6	Class D Amplifiers	414
10.7	Thermal Management of Power Transistors	417
	Key Terms	418
	Objective-Type Exercises	419
	Review Questions	421
	Problems	421
	Answers	422
11	Feedback Amplifiers	423
11.1	Classification of Amplifiers	423
11.2	Amplifier with Negative Feedback	425
	<i>Effect of Negative Feedback on Gain</i>	426
11.3	Advantages of Negative Feedback	429
	<i>Desensitivity (or Stability) of Gain</i>	430
	<i>Effect on Bandwidth</i>	430
	<i>Effect on Non-Linear Distortion</i>	431
	<i>Effect on Noise</i>	431
	<i>Effect on Input Resistance</i>	432
	<i>Effect on Output Resistance</i>	432
11.4	Feedback Topologies	434
11.5	Voltage-Series (Series–Shunt) Feedback	434
11.6	Voltage-Shunt (Shunt–Shunt) Feedback	440
11.7	Current-Series (Series–Series) Feedback	443
11.8	Current-Shunt (Shunt–Series) Feedback	448
	Key Terms	452
	Objective-Type Exercises	452
	Review Questions	454
	Problems	455
	Answers	456
12	Sinusoidal Oscillators	457
12.1	Classification of Oscillators	457
12.2	Conditions for Oscillations: Barkhausen Criterion	458
	<i>Initiation of Oscillations</i>	459
12.3	Types of Oscillators	460
	<i>RC Oscillators</i>	460
	<i>LC Oscillators</i>	460
	<i>Crystal Oscillators</i>	460
12.4	RC Phase Shift Oscillator	461
12.5	Buffered RC Phase Shift Oscillator	465
12.6	Bubba Oscillator	467

12.7	Quadrature Oscillator	468
12.8	Twin-T Oscillator	469
12.9	Wien Bridge Oscillator	471
	<i>Distortion in Wien Bridge Oscillator</i>	473
12.10	LC Oscillators	479
12.11	Armstrong Oscillator	479
12.12	Hartley Oscillator	481
12.13	Colpitt Oscillator	483
12.14	Clapp Oscillator	484
12.15	Crystal Oscillator	488
	<i>AC Equivalent Circuit of a Quartz Crystal</i>	489
	<i>Extremely High Frequency Stability</i>	490
	<i>Crystal Oscillator Circuits</i>	490
12.16	Voltage-Controlled Oscillators	493
12.17	Frequency Stability	494
	<i>Frequency Stability Criterion</i>	494
	Key Terms	495
	Objective-Type Exercises	496
	Review Questions	498
	Problems	499
	Answers	501
13	Wave-Shaping Circuits	503
13.1	Basic RC Low-Pass Circuit	503
	<i>Step Input</i>	504
	<i>Pulse Input</i>	505
13.2	RC Low-Pass Circuit as Integrator	505
13.3	Basic RC High-Pass Circuit	509
13.4	RC High-Pass Circuit as Differentiator	511
13.5	Basic RL Circuit as Integrator	512
13.6	Basic RL Circuit as Differentiator	513
13.7	Diode Clipper Circuits	514
13.8	Diode Clamper Circuits	520
	<i>Negative Clamper</i>	520
	<i>Positive Clamper</i>	522
13.9	Multivibrators	527
	<i>Bistable Multivibrator</i>	527
	<i>Schmitt Trigger</i>	529
	<i>Monostable Multivibrator</i>	530
	<i>Astable Multivibrator</i>	531
13.10	Integrated Circuit (IC) Multivibrators	535
	<i>Digital IC-Based Monostable Multivibrators</i>	535
	<i>Timer IC-Based Multivibrators</i>	535
	Key Terms	543
	Objective-Type Exercises	543
	Review Questions	544

Problems	545
Answers	546
14 Linear Power Supplies	547
14.1 Constituents of a Linear Power Supply	547
14.2 Designing Mains Transformer	548
14.3 Rectifier Circuits	550
<i>Characteristic Parameters</i>	550
<i>Half-Wave Rectifier</i>	552
<i>Full-Wave Rectifier</i>	553
<i>Bridge Rectifier</i>	555
14.4 Filters	558
<i>Inductor Filter</i>	558
<i>Capacitor Filter</i>	559
<i>LC Filter</i>	561
<i>CLC Filter (π-Filter)</i>	563
14.5 Linear Regulators	565
<i>Emitter-Follower Regulator</i>	565
<i>Series-Pass Regulator</i>	566
<i>Current Limiting</i>	568
<i>Shunt Regulator</i>	571
14.6 Linear IC Voltage Regulators	576
<i>General-Purpose Precision Linear Voltage Regulator</i>	576
<i>Three-Terminal Regulators</i>	577
<i>Boosting Current Delivery Capability</i>	579
14.7 Regulated Power Supply Parameters	582
<i>Load Regulation</i>	582
<i>Line Regulation</i>	582
<i>Output Impedance</i>	582
<i>Ripple Rejection Factor</i>	582
Key Terms	584
Objective-Type Exercises	585
Review Questions	587
Problems	588
Answers	590
15 Switched Mode Power Supplies	591
15.1 Switched Mode Power Supplies	591
<i>Linear versus Switched Mode Power Supplies</i>	592
<i>Different Types of SMPS</i>	592
15.2 Flyback Converters	593
<i>Self-Oscillating Flyback DC-to-DC Converter</i>	593
<i>Externally Driven Flyback DC-to-DC Converter</i>	594
<i>Discontinuous and Continuous Operational Modes</i>	597
<i>Design Procedure for Externally Driven Flyback DC-to-DC Converter</i>	599

15.3	Forward Converter	604
15.4	Push–Pull Converter	605
	<i>Design Procedure for Push–Pull DC-to-DC Converter</i>	608
15.5	Switching Regulators	613
	<i>Buck Regulator</i>	613
	<i>Boost Regulator</i>	615
	<i>Inverting Regulator</i>	616
	<i>Three-Terminal Switching Regulators</i>	617
15.6	Connecting Power Converters in Series	618
15.7	Connecting Power Converters in Parallel	618
	Key Terms	621
	Objective-Type Exercises	621
	Review Questions	624
	Problems	624
	Answers	625
16	Introduction to Operational Amplifiers	627
16.1	Operational Amplifier	627
16.2	Inside of the Opamp	628
	<i>Differential Amplifier Input Stage</i>	629
16.3	Ideal Opamp versus Practical Opamp	634
16.4	Performance Parameters	636
	<i>Bandwidth</i>	636
	<i>Slew Rate</i>	638
	<i>Open-Loop Gain</i>	638
	<i>Common Mode Rejection Ratio</i>	639
	<i>Power Supply Rejection Ratio</i>	639
	<i>Input Impedance</i>	641
	<i>Output Impedance</i>	641
	<i>Settling Time</i>	641
	<i>Offsets and Offset Drifts</i>	642
16.5	Types of Opamps	643
	<i>General-Purpose Opamps</i>	644
	<i>High-Speed Opamps</i>	644
	<i>Precision Opamps</i>	644
	<i>Power Opamps</i>	644
	<i>Opamps Comparators</i>	644
	<i>Norton Opamps</i>	645
	<i>Instrumentation Opamps</i>	645
	<i>Isolation Opamps</i>	646
	Key Terms	647
	Objective-Type Exercises	648
	Review Questions	649
	Problems	649
	Answers	650

17	Operational Amplifier Application Circuits	651
17.1	Inverting Amplifier	652
	<i>Design Information</i>	653
17.2	Non-Inverting Amplifier	654
	<i>Design Information</i>	654
17.3	Voltage Follower	655
17.4	Summing Amplifier	659
17.5	Difference Amplifier	661
17.6	Averager	662
17.7	Integrator	663
17.8	Differentiator	664
17.9	Rectifier Circuits	667
17.10	Clipper Circuits	668
17.11	Clamper Circuits	669
17.12	Peak Detector Circuit	670
17.13	Absolute Value Circuit	671
17.14	Comparator	672
	<i>Opamp Comparator</i>	674
	<i>Comparator with Hysteresis</i>	674
	<i>Window Comparator</i>	676
17.15	Active Filters	680
	<i>First-Order Filters</i>	680
	<i>Second-Order Filters</i>	681
17.16	Phase Shifters	685
17.17	Instrumentation Amplifier	687
17.18	Non-Linear Amplifier	689
17.19	Relaxation Oscillator	690
17.20	Current-To-Voltage Converter	691
17.21	Voltage-To-Current Converter	692
17.22	Sine Wave Oscillators	694
	Key Terms	694
	Objective-Type Exercises	694
	Review Questions	696
	Problems	697
	Answers	699
	Index	701