

Contents

1 INTRODUCTION TO MICROELECTRONICS 1

- 1.1 Electronics versus Microelectronics 1
- 1.2 Examples of Electronic Systems 2
 - 1.2.1 Cellular Telephone 2
 - 1.2.2 Digital Camera 5
 - 1.2.3 Analog Versus Digital 7
- 1.3 Basic Concepts 8
 - 1.3.1 Analog and Digital Signals 8
 - 1.3.2 Analog Circuits 10
 - 1.3.3 Digital Circuits 11
 - 1.3.4 Basic Circuit Theorems 13
- 1.4 Chapter Summary 20

2 BASIC PHYSICS OF SEMICONDUCTORS 21

- 2.1 Semiconductor Materials and Their Properties 22
 - 2.1.1 Charge Carriers in Solids 22
 - 2.1.2 Modification of Carrier Densities 25
 - 2.1.3 Transport of Carriers 28
- 2.2 *pn* Junction 36
 - 2.2.1 *pn* Junction in Equilibrium 37
 - 2.2.2 *pn* Junction Under Reverse Bias 42
 - 2.2.3 *pn* Junction Under Forward Bias 46
 - 2.2.4 I/V Characteristics 49
- 2.3 Reverse Breakdown 54
 - 2.3.1 Zener Breakdown 54
 - 2.3.2 Avalanche Breakdown 55
- 2.4 Chapter Summary 55
 - Problems 56
 - SPICE Problems 60

3 DIODE MODELS AND CIRCUITS 62

- 3.1 Ideal Diode 62
 - 3.1.1 Initial Thoughts 62
 - 3.1.2 Ideal Diode 64
 - 3.1.3 Application Examples 68

- 3.2 *pn* Junction as a Diode 73
- 3.3 Additional Examples 75
- 3.4 Large-Signal and Small-Signal Operation 80
- 3.5 Applications of Diodes 89
 - 3.5.1 Half-Wave and Full-Wave Rectifiers 89
 - 3.5.2 Voltage Regulation 102
 - 3.5.3 Limiting Circuits 104
 - 3.5.4 Voltage Doublers 108
 - 3.5.5 Diodes as Level Shifters and Switches 112
- 3.6 Chapter Summary 115
 - Problems 116
 - SPICE Problems 126

4 PHYSICS OF BIPOLAR TRANSISTORS 128

- 4.1 General Considerations 128
- 4.2 Structure of Bipolar Transistor 130
- 4.3 Operation of Bipolar Transistor in Active Mode 131
 - 4.3.1 Collector Current 134
 - 4.3.2 Base and Emitter Currents 137
- 4.4 Bipolar Transistor Models and Characteristics 139
 - 4.4.1 Large-Signal Model 139
 - 4.4.2 I/V Characteristics 141
 - 4.4.3 Concept of Transconductance 143
 - 4.4.4 Small-Signal Model 145
 - 4.4.5 Early Effect 150
- 4.5 Operation of Bipolar Transistor in Saturation Mode 156
- 4.6 The *PNP* Transistor 159
 - 4.6.1 Structure and Operation 160
 - 4.6.2 Large-Signal Model 160
 - 4.6.3 Small-Signal Model 163
- 4.7 Chapter Summary 167
 - Problems 167
 - SPICE Problems 178

5 BIPOLAR AMPLIFIERS 181

- 5.1 General Considerations 181
 - 5.1.1 Input and Output Impedances 182
 - 5.1.2 Biasing 186
 - 5.1.3 DC and Small-Signal Analysis 186
- 5.2 Operating Point Analysis and Design 188
 - 5.2.1 Simple Biasing 189
 - 5.2.2 Resistive Divider Biasing 192
 - 5.2.3 Biasing with Emitter Degeneration 195
 - 5.2.4 Self-Biased Stage 199
 - 5.2.5 Biasing of *PNP* Transistors 202
- 5.3 Bipolar Amplifier Topologies 206
 - 5.3.1 Common-Emitter Topology 207
 - 5.3.2 Common-Base Topology 233
 - 5.3.3 Emitter Follower 250
- 5.4 Summary and Additional Examples 258
- 5.5 Chapter Summary 264
 - Problems 264
 - SPICE Problems 285

6 PHYSICS OF MOS TRANSISTORS 288

- 6.1 Structure of MOSFET 288
- 6.2 Operation of MOSFET 291
 - 6.2.1 Qualitative Analysis 291
 - 6.2.2 Derivation of I/V Characteristics 297
 - 6.2.3 Channel-Length Modulation 306
 - 6.2.4 MOS Transconductance 308
 - 6.2.5 Velocity Saturation 310
 - 6.2.6 Other Second-Order Effects 310
- 6.3 MOS Device Models 311
 - 6.3.1 Large-Signal Model 311
 - 6.3.2 Small-Signal Model 313
- 6.4 PMOS Transistor 314
- 6.5 CMOS Technology 316
- 6.6 Comparison of Bipolar and MOS Devices 317
- 6.7 Chapter Summary 317
 - Problems 318
 - SPICE Problems 327

7 CMOS AMPLIFIERS 329

- 7.1 General Considerations 329
 - 7.1.1 MOS Amplifier Topologies 329
 - 7.1.2 Biasing 329
 - 7.1.3 Realization of Current Sources 333
- 7.2 Common-Source Stage 334
 - 7.2.1 CS Core 334
 - 7.2.2 CS Stage With Current-Source Load 337
 - 7.2.3 CS Stage With Diode-Connected Load 338
 - 7.2.4 CS Stage With Degeneration 340
 - 7.2.5 CS Core With Biasing 343
- 7.3 Common-Gate Stage 345
 - 7.3.1 CG Stage With Biasing 350
- 7.4 Source Follower 351
 - 7.4.1 Source Follower Core 352
 - 7.4.2 Source Follower With Biasing 354
- 7.5 Summary and Additional Examples 356
- 7.6 Chapter Summary 360
 - Problems 360
 - SPICE Problems 378

8 OPERATIONAL AMPLIFIER AS A BLACK BOX 380

- 8.1 General Considerations 381
- 8.2 Op-Amp-Based Circuits 383
 - 8.2.1 Noninverting Amplifier 383
 - 8.2.2 Inverting Amplifier 385
 - 8.2.3 Integrator and Differentiator 388
 - 8.2.4 Voltage Adder 395
- 8.3 Nonlinear Functions 396
 - 8.3.1 Precision Rectifier 396
 - 8.3.2 Logarithmic Amplifier 397
 - 8.3.3 Square-Root Amplifier 398
- 8.4 Op Amp Nonidealities 399
 - 8.4.1 DC Offsets 399
 - 8.4.2 Input Bias Current 402
 - 8.4.3 Speed Limitations 405
 - 8.4.4 Finite Input and Output Impedances 410

- 8.5 Design Examples 411
- 8.6 Chapter Summary 413
 - Problems 414
 - SPICE Problems 423
- 9 CASCODE STAGES AND CURRENT MIRRORS 425**
 - 9.1 Cascode Stage 425
 - 9.1.1 Cascode as a Current Source 425
 - 9.1.2 Cascode as an Amplifier 432
 - 9.2 Current Mirrors 441
 - 9.2.1 Initial Thoughts 441
 - 9.2.2 Bipolar Current Mirror 442
 - 9.2.3 MOS Current Mirror 451
 - 9.3 Chapter Summary 454
 - Problems 455
 - SPICE Problems 470
- 10 DIFFERENTIAL AMPLIFIERS 473**
 - 10.1 General Considerations 473
 - 10.1.1 Initial Thoughts 473
 - 10.1.2 Differential Signals 475
 - 10.1.3 Differential Pair 478
 - 10.2 Bipolar Differential Pair 479
 - 10.2.1 Qualitative Analysis 479
 - 10.2.2 Large-Signal Analysis 484
 - 10.2.3 Small-Signal Analysis 488
 - 10.3 MOS Differential Pair 494
 - 10.3.1 Qualitative Analysis 495
 - 10.3.2 Large-Signal Analysis 499
 - 10.3.3 Small-Signal Analysis 503
 - 10.4 Cascode Differential Amplifiers 507
 - 10.5 Common-Mode Rejection 511
 - 10.6 Differential Pair with Active Load 515
 - 10.6.1 Qualitative Analysis 516
 - 10.6.2 Quantitative Analysis 518
 - 10.7 Chapter Summary 523
 - Problems 524
 - SPICE Problems 541
- 11 FREQUENCY RESPONSE 544**
 - 11.1 Fundamental Concepts 544
 - 11.1.1 General Considerations 544
 - 11.1.2 Relationship Between Transfer Function and Frequency Response 547
 - 11.1.3 Bode's Rules 550
 - 11.1.4 Association of Poles with Nodes 551
 - 11.1.5 Miller's Theorem 553
 - 11.1.6 General Frequency Response 556
 - 11.2 High-Frequency Models of Transistors 559
 - 11.2.1 High-Frequency Model of Bipolar Transistor 559
 - 11.2.2 High-Frequency Model of MOSFET 561
 - 11.2.3 Transit Frequency 563
 - 11.3 Analysis Procedure 564
 - 11.4 Frequency Response of CE and CS Stages 565
 - 11.4.1 Low-Frequency Response 565
 - 11.4.2 High-Frequency Response 566
 - 11.4.3 Use of Miller's Theorem 566
 - 11.4.4 Direct Analysis 569
 - 11.4.5 Input Impedance 572
 - 11.5 Frequency Response of CB and CG Stages 573
 - 11.5.1 Low-Frequency Response 573
 - 11.5.2 High-Frequency Response 574
 - 11.6 Frequency Response of Followers 576
 - 11.6.1 Input and Output Impedances 580
 - 11.7 Frequency Response of Cascode Stage 583
 - 11.7.1 Input and Output Impedances 587
 - 11.8 Frequency Response of Differential Pairs 588
 - 11.8.1 Common-Mode Frequency Response 590
 - 11.9 Additional Examples 591
 - 11.10 Chapter Summary 595
 - Problems 596
 - SPICE Problems 607

12 FEEDBACK 610

- 12.1 General Considerations 610
 - 12.1.1 Loop Gain 613
- 12.2 Properties of Negative Feedback 614
 - 12.2.1 Gain Desensitization 614
 - 12.2.2 Bandwidth Extension 616
 - 12.2.3 Modification of I/O Impedances 618
 - 12.2.4 Linearity Improvement 622
- 12.3 Types of Amplifiers 622
 - 12.3.1 Simple Amplifier Models 623
 - 12.3.2 Examples of Amplifier Types 624
- 12.4 Sense and Return Techniques 626
- 12.5 Polarity of Feedback 629
- 12.6 Feedback Topologies 631
 - 12.6.1 Voltage-Voltage Feedback 631
 - 12.6.2 Voltage-Current Feedback 636
 - 12.6.3 Current-Voltage Feedback 639
 - 12.6.4 Current-Current Feedback 644
- 12.7 Effect of Nonideal I/O Impedances 647
 - 12.7.1 Inclusion of I/O Effects 648
- 12.8 Stability in Feedback Systems 660
 - 12.8.1 Review of Bode's Rules 660
 - 12.8.2 Problem of Instability 662
 - 12.8.3 Stability Condition 665
 - 12.8.4 Phase Margin 668
 - 12.8.5 Frequency Compensation 670
 - 12.8.6 Miller Compensation 673
- 12.9 Chapter Summary 674
 - Problems 675
 - SPICE Problems 691

13 OUTPUT STAGES AND POWER AMPLIFIERS 694

- 13.1 General Considerations 694
- 13.2 Emitter Follower as Power Amplifier 695
- 13.3 Push-Pull Stage 698
- 13.4 Improved Push-Pull Stage 701
 - 13.4.1 Reduction of Crossover Distortion 701
 - 13.4.2 Addition of CE Stage 705

- 13.5 Large-Signal Considerations 708
 - 13.5.1 Biasing Issues 708
 - 13.5.2 Omission of PNP Power Transistor 709
 - 13.5.3 High-Fidelity Design 712
- 13.6 Short-Circuit Protection 713
- 13.7 Heat Dissipation 713
 - 13.7.1 Emitter Follower Power Rating 714
 - 13.7.2 Push-Pull Stage Power Rating 715
 - 13.7.3 Thermal Runaway 716
- 13.8 Efficiency 718
 - 13.8.1 Efficiency of Emitter Follower 718
 - 13.8.2 Efficiency of Push-Pull Stage 719
- 13.9 Power Amplifier Classes 720
- 13.10 Chapter Summary 721
 - Problems 722
 - SPICE Problems 728

14 ANALOG FILTERS 731

- 14.1 General Considerations 731
 - 14.1.1 Filter Characteristics 732
 - 14.1.2 Classification of Filters 733
 - 14.1.3 Filter Transfer Function 737
 - 14.1.4 Problem of Sensitivity 740
- 14.2 First-Order Filters 741
- 14.3 Second-Order Filters 744
 - 14.3.1 Special Cases 744
 - 14.3.2 RLC Realizations 748
- 14.4 Active Filters 753
 - 14.4.1 Sallen and Key Filter 753
 - 14.4.2 Integrator-Based Biquads 758
 - 14.4.3 Biquads Using Simulated Inductors 762
- 14.5 Approximation of Filter Response 768
 - 14.5.1 Butterworth Response 768
 - 14.5.2 Chebyshev Response 772
- 14.6 Chapter Summary 777
 - Problems 778
 - SPICE Problems 784

15 DIGITAL CMOS CIRCUITS 786

- 15.1 General Considerations 786**
 - 15.1.1 Static Characterization of Gates 787
 - 15.1.2 Dynamic Characterization of Gates 794
 - 15.1.3 Power-Speed Trade-Off 797
- 15.2 CMOS Inverter 799**
 - 15.2.1 Initial Thoughts 799
 - 15.2.2 Voltage Transfer Characteristic 801
 - 15.2.3 Dynamic Characteristics 807
 - 15.2.4 Power Dissipation 812
- 15.3 CMOS NOR and NAND Gates 816**
 - 15.3.1 NOR Gate 816
 - 15.3.2 NAND Gate 819
- 15.4 Chapter Summary 820**
 - Problems 821
 - SPICE Problems 827

16 CMOS AMPLIFIERS* 829

- 16.1 General Considerations 829**
 - 16.1.1 Input and Output Impedances 830
 - 16.1.2 Biasing 834
 - 16.1.3 DC and Small-Signal Analysis 835

16.2 Operating Point Analysis and Design 836

- 16.2.1 Simple Biasing 838
- 16.2.2 Biasing with Source Degeneration 840
- 16.2.3 Self-Biased Stage 843
- 16.2.4 Biasing of PMOS Transistors 844
- 16.2.5 Realization of Current Sources 845
- 16.3 CMOS Amplifier Topologies 846**
- 16.4 Common-Source Topology 847**
 - 16.4.1 CS Stage with Current-Source Load 852
 - 16.4.2 CS Stage with Diode-Connected Load 853
 - 16.4.3 CS Stage with Source Degeneration 854
 - 16.4.4 Common-Gate Topology 866
 - 16.4.5 Source Follower 877
- 16.5 Additional Examples 883**
- 16.6 Chapter Summary 887**
 - Problems 888
 - SPICE Problems 906

Appendix A INTRODUCTION TO SPICE 909