# Practical Considerations

## 1 Introduction

1.0 *Introduction*  
1.1 Size and Complexity of Integrated Circuits  
1.2 The Microelectronics Field  
1.3 IC Design Process  
1.4 Economics  
1.5 Yield  
1.6 Trends in VLSI Design

## References

## Problems

# Technology

## 2 Introduction

2.0 *Introduction*  
2.1 IC Production Process  
  2.1.1 Processing Steps  
  2.1.2 Packaging and Testing  
2.2 Semiconductor Processes  
  2.2.1 MOS Processes  
    2.2.1a NMOS Process  
    2.2.1b CMOS Process  
    2.2.1c Practical Process Considerations  
  2.2.2 Bipolar Technology  
  2.2.3 Hybrid Technology  
2.3 Design Rules and Process Parameters  
2.4 Layout Techniques and Practical Considerations

## References

## Problems

# Appendixes

## 2A Process Characterization of a Generic NMOS Process  
## 2B Process Characterization of a Generic CMOS Process
3 Device Modeling

3.0 Modeling
3.0.1 dc Models
3.0.2 Small Signal Models
3.0.3 Use of Device Models in Circuit Analysis
3.1 MOS Models
3.1.1 dc MOSFET Model
3.1.2 Small Signal MOSFET Model
3.1.3 High Frequency MOSFET Model
3.1.4 Measurement of MOSFET Model Parameters
3.1.5 Short Channel Devices
3.1.6 Subthreshold Operation
3.1.7 Operation in the Third Quadrant of the $I_D - V_{DS}$ Plane
3.1.8 Modeling Noise Sources in MOSFETs
3.1.9 Simple MOSFET Models for Digital Applications
3.2 Diode Models
3.2.1 dc Diode Model
3.2.2 Small Signal Diode Model
3.2.3 High-Frequency Diode Model
3.3 Bipolar Models
3.3.1 dc BJT Model
3.3.2 Small Signal BJT Model
3.3.3 High-Frequency BJT Model
3.3.4 Measurement of BJT Model Parameters
3.4 Passive Component Models
3.4.1 Monolithic Capacitors
3.4.2 Monolithic Resistors
3.5 Summary

4 Circuit Simulation

4.0 Introduction
4.1 Circuit Simulation Using Spice
4.2 MOSFET Model
4.2.1 Level 1 Large Signal Model
4.2.2 Level 2 Large Signal Model
4.2.3 High-Frequency Model
4.2.4 Noise Model of the MOSFET
4.2.5 Temperature Dependence of the MOSFET
4.3 Diode Model
4.3.1 Large Signal Diode Current
4.3.2 High-Frequency Diode Model
4.4 BJT Model
4.4.1 Large Signal BJT Model
4.4.2 High-Frequency BJT Model
6.6 Comparators
6.6.1 Characterization of Comparators 499
6.6.2 High-Gain Comparators 502
6.6.3 Propagation Delay of Two-Stage Comparators 507
6.6.4 Comparators Using Positive Feedback 511
6.6.5 Autozeroing 514
6.7 Summary 518
References 518
Problems 519
Design Problems 524

7 Digital Circuits 525
7.0 Introduction 525
7.1 Design Abstraction 526
7.2 Characteristics of Digital Circuits 528
7.2.1 Logic Level Standards 528
7.2.2 Inverter Pair Characteristics 530
7.2.3 Logic Fan-out Characteristics 532
7.2.4 Digital Logic Analysis 532
7.3 Single-Channel MOS Inverters 534
7.3.1 Basic Inverter 534
7.3.2 Inverter Device Sizing 537
7.3.3 Enhancement-Load versus Depletion-Load Inverters 539
7.4 NMOS NOR and NAND Logic Circuits 540
7.4.1 Basic NMOS NOR Logic Circuits 540
7.4.2 Basic NMOS NAND Logic Circuits 542
7.4.3 Multi-Input NAND and NOR Logic Circuits 543
7.5 Complementary MOS Inverters 544
7.5.1 A Basic CMOS Inverter 546
7.5.2 CMOS Inverter Logic Levels 546
7.5.3 Inverter Device Sizing 548
7.6 CMOS Logic Gates 551
7.6.1 CMOS NOR Logic Gate 551
7.6.2 CMOS NAND Logic Gate 553
7.6.3 Multi-Input CMOS Logic Gates 556
7.7 Transmission Gates 558
7.7.1 NMOS Pass Transistor 559
7.7.2 CMOS Transmission Gate 562
7.8 Signal Propagation Delays 564
7.8.1 Ratio-Logic Model 565
7.8.2 Process Characteristic Time Constant 570
7.8.3 Inverter-Pair Delay 570
7.8.4 Superbuffers 573
7.8.5 NMOS NAND and NOR Delays 575
7.8.6 Enhancement versus Depletion Loads 578
7.8.7 CMOS Logic Delays 579
7.8.8 Interconnection Characteristics 582
7.9 Capacitive Loading Considerations 584
7.9.1 Capacitive Loading 584
7.9.2 Logic Fan-out Delays 585
CONTENTS

7.9.3 Distributed Drivers 587
7.9.4 Driving Off-Chip Loads 588
7.9.5 Cascaded Drivers 590
7.10 Power Dissipation 593
7.10.1 NMOS Power Dissipation 595
7.10.2 CMOS Power Dissipation 597
7.11 Noise in Digital Logic Circuits 599
7.11.1 Resistive Noise Coupling 599
7.11.2 Capacitive Noise Coupling 601
7.11.3 Definition of Noise Margins 602
7.11.4 NMOS Noise Margins 603
7.11.5 CMOS Noise Margins 605
7.12 Summary 607
References 608
Problems 608

8 Analog Systems 612
8.0 Introduction 612
8.1 Analog Signal Processing 612
8.2 Digital-to-Analog Converters 615
8.2.1 Current-Scaling D/A Converters 623
8.2.2 Voltage-Scaling D/A Converters 626
8.2.3 Charge-Scaling D/A Converters 629
8.2.4 D/A Converters Using Combinations of Scaling Approaches 633
8.2.5 Serial D/A Converters 638
8.3 Analog-to-Digital Converters 642
8.3.1 Serial A/D Converters 648
8.3.2 Successive Approximation A/D Converters 651
8.3.3 Parallel A/D Converters 659
8.3.4 High-Performance A/D Converters 664
8.3.5 Summary 671
8.4 Continuous-Time Filters 673
8.4.1 Low-Pass Filters 674
8.4.2 High-Pass Filters 685
8.4.3 Bandpass Filters 688
8.5 Switched Capacitor Filters 692
8.5.1 Resistor Realization 693
8.5.2 Passive RLC Prototype Switched Capacitor Filters 703
8.5.3 Z-Domain Synthesis Techniques 716
8.6 Analog Signal Processing Circuits 729
8.6.1 Precision Breakpoint Circuits 729
8.6.2 Modulators and Multipliers 735
8.6.3 Oscillators 747
8.6.4 Phase-Locked Loops 762
8.7 Summary 765
References 770
Problems 773

9 Structured Digital Circuits and Systems 778
9.0 Introduction 778
9.1 Random Logic versus Structured Logic Forms 779
9.2 Programmable Logic Arrays 783
  9.2.1 PLA Organization 784
  9.2.2 Automatic PLA Generation 790
  9.2.3 Folded PLAs 791
  9.2.4 Large PLAs 792
9.3 Structured Gate Layout 793
  9.3.1 Weinberger Arrays 794
  9.3.2 Gate Matrix Layout 796
9.4 Logic Gate Arrays 799
9.5 MOS Clocking Schemes 805
9.6 Dynamic MOS Storage Circuits 808
  9.6.1 Dynamic Charge Storage 808
  9.6.2 Simple Shift Register 811
  9.6.3 Other Shift Registers 814
9.7 Clocked CMOS Logic 815
  9.7.1 C2MOS 815
  9.7.2 Precharge-Evaluate Logic 817
  9.7.3 Domino CMOS 819
9.8 Semiconductor Memories 821
  9.8.1 Memory Organization 822
9.9 Read-Only Memory 824
  9.9.1 Erasable Programmable Read-Only Memory 825
  9.9.2 Electrically Erasable Programmable Read-Only Memory 826
9.10 Static RAM Memories 827
9.11 Dynamic RAM Memory 835
9.12 Register Storage Circuits 839
  9.12.1 Quasi-Static Register Cells 840
  9.12.2 A Static Register Cell 842
9.13 PLA-Based Finite-State Machines 845
9.14 Microcoded Controllers 848
9.15 Microprocessor Design 853
  9.15.1 Data Path Description 856
  9.15.2 Barrel Shifter 857
  9.15.3 Arithmetic Logic Unit 858
  9.15.4 Microcoded Controller 860
9.16 Systolic Arrays 861
  9.16.1 Systolic Matrix Multiplication 861
  9.16.2 General Linear System Solver 862
  9.16.3 Bit-Serial Processing Elements 863
9.17 Summary 866
References 866
Problems 867

10 Design Automation and Verification 872
10.0 Introduction 872
10.1 Integrated Circuit Layout 873
  10.1.1 Geometrical Specification Languages 875
  10.1.2 Layout Styles 878
10.2 Symbolic Circuit Representation 880
  10.2.1 Parameterized Layout Representation 880
  10.2.2 Parameterized Module Generation 883