Brief Contents

Chapter 1 Introduction to CMOS Design 1
Chapter 2 The Well 31
Chapter 3 The Metal Layers 59
Chapter 4 The Active and Poly Layers 83
Chapter 5 Resistors, Capacitors, MOSFETs 107
Chapter 6 MOSFET Operation 135
Chapter 7 CMOS Fabrication by Jeff Jessing 165
Chapter 8 Electrical Noise: An Overview 221
Chapter 9 Models for Analog Design 277
Chapter 10 Models for Digital Design 327
Chapter 11 The Inverter 347
Chapter 12 Static Logic Gates 369
Chapter 13 Clocked Circuits 389
Chapter 14 Dynamic Logic Gates 411
Chapter 15 CMOS Layout Examples 425
Chapter 16 Memory Circuits 445
Chapter 17 Sensing Using ΔΣ Modulation 493
Chapter 18 Special Purpose CMOS Circuits 533
Chapter 19 Digital Phase-Locked Loops 561
Chapter 20 Current Mirrors 621
Chapter 21 Amplifiers 671
Chapter 22 Differential Amplifiers 735
Chapter 23 Voltage References 773
Chapter 24 Operational Amplifiers I 803
Chapter 25 Dynamic Analog Circuits 857
Chapter 26 Operational Amplifiers II 889
Chapter 27 Nonlinear Analog Circuits 933
Chapter 28 Data Converter Fundamentals by Harry Li 955
Chapter 29 Data Converter Architectures by Harry Li 987
Chapter 30 Implementing Data Converters 1043
Chapter 31 Feedback Amplifiers with Harry Li 1115
Chapter 32 Hysteretic Power Converters 1175
# Contents

## Preface

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>xxxiii</td>
</tr>
</tbody>
</table>

## Chapter 1 Introduction to CMOS Design

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 The CMOS IC Design Process</td>
<td>1</td>
</tr>
<tr>
<td>1.1.1 Fabrication</td>
<td>2</td>
</tr>
<tr>
<td>Layout and Cross-Sectional Views</td>
<td>5</td>
</tr>
<tr>
<td>1.2 CMOS Background</td>
<td>5</td>
</tr>
<tr>
<td>The CMOS Acronym</td>
<td>6</td>
</tr>
<tr>
<td>CMOS Inverter</td>
<td>6</td>
</tr>
<tr>
<td>The First CMOS Circuits</td>
<td>7</td>
</tr>
<tr>
<td>Analog Design in CMOS</td>
<td>7</td>
</tr>
<tr>
<td>1.3 An Introduction to SPICE</td>
<td>8</td>
</tr>
<tr>
<td>Generating a Netlist File</td>
<td>8</td>
</tr>
<tr>
<td>Operating Point</td>
<td>8</td>
</tr>
<tr>
<td>Transfer Function Analysis</td>
<td>10</td>
</tr>
<tr>
<td>The Voltage-Controlled Voltage Source</td>
<td>10</td>
</tr>
<tr>
<td>An Ideal Op-Amp</td>
<td>11</td>
</tr>
<tr>
<td>The Subcircuit</td>
<td>12</td>
</tr>
<tr>
<td>DC Analysis</td>
<td>13</td>
</tr>
<tr>
<td>Plotting IV Curves</td>
<td>13</td>
</tr>
<tr>
<td>Dual Loop DC Analysis</td>
<td>14</td>
</tr>
<tr>
<td>Transient Analysis</td>
<td>14</td>
</tr>
<tr>
<td>The SIN Source</td>
<td>15</td>
</tr>
<tr>
<td>An RC Circuit Example</td>
<td>16</td>
</tr>
<tr>
<td>Another RC Circuit Example</td>
<td>17</td>
</tr>
<tr>
<td>AC Analysis</td>
<td>18</td>
</tr>
<tr>
<td>Decades and Octaves</td>
<td>19</td>
</tr>
<tr>
<td>Decibels</td>
<td>19</td>
</tr>
<tr>
<td>Pulse Statement</td>
<td>20</td>
</tr>
<tr>
<td>Finite Pulse Rise time</td>
<td>20</td>
</tr>
<tr>
<td>Topic</td>
<td>Page</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Step Response</td>
<td>21</td>
</tr>
<tr>
<td>Delay and Rise time in RC Circuits</td>
<td>21</td>
</tr>
<tr>
<td>Piece-Wise Linear (PWL) Source</td>
<td>22</td>
</tr>
<tr>
<td>Simulating Switches</td>
<td>22</td>
</tr>
<tr>
<td>Initial Conditions on a Capacitor</td>
<td>23</td>
</tr>
<tr>
<td>Initial Conditions in an Inductor</td>
<td>23</td>
</tr>
<tr>
<td>Q of an LC Tank</td>
<td>24</td>
</tr>
<tr>
<td>Frequency Response of an Ideal Integrator</td>
<td>24</td>
</tr>
<tr>
<td>Unity-Gain Frequency</td>
<td>26</td>
</tr>
<tr>
<td>Time-Domain Behavior of the Integrator</td>
<td>26</td>
</tr>
<tr>
<td>Convergence</td>
<td>26</td>
</tr>
<tr>
<td>Some Common Mistakes and Helpful Techniques</td>
<td>27</td>
</tr>
</tbody>
</table>

**Chapter 2 The Well**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Substrate (The Unprocessed Wafer)</td>
<td>31</td>
</tr>
<tr>
<td>A Parasitic Diode</td>
<td>31</td>
</tr>
<tr>
<td>Using the N-well as a Resistor</td>
<td>32</td>
</tr>
<tr>
<td>2.1 Patterning</td>
<td>32</td>
</tr>
<tr>
<td>2.1.1 Patterning the N-well</td>
<td>35</td>
</tr>
<tr>
<td>2.2 Laying Out the N-well</td>
<td>35</td>
</tr>
<tr>
<td>2.2.1 Design Rules for the N-well</td>
<td>36</td>
</tr>
<tr>
<td>2.3 Resistance Calculation</td>
<td>36</td>
</tr>
<tr>
<td>2.3.1 The N-well Resistor</td>
<td>38</td>
</tr>
<tr>
<td>2.4 The N-well/Substrate Diode</td>
<td>39</td>
</tr>
<tr>
<td>2.4.1 A Brief Introduction to PN Junction Physics</td>
<td>39</td>
</tr>
<tr>
<td>Carrier Concentrations</td>
<td>40</td>
</tr>
<tr>
<td>Fermi Energy Level</td>
<td>41</td>
</tr>
<tr>
<td>2.4.2 Depletion Layer Capacitance</td>
<td>42</td>
</tr>
<tr>
<td>2.4.3 Storage or Diffusion Capacitance</td>
<td>45</td>
</tr>
<tr>
<td>2.4.4 SPICE Modeling</td>
<td>46</td>
</tr>
<tr>
<td>2.5 The RC Delay through the N-well</td>
<td>48</td>
</tr>
<tr>
<td>RC Circuit Review</td>
<td>48</td>
</tr>
<tr>
<td>Distributed RC Delay</td>
<td>50</td>
</tr>
<tr>
<td>Distributed RC Rise Time</td>
<td>51</td>
</tr>
<tr>
<td>2.6 Twin Well Processes</td>
<td>51</td>
</tr>
<tr>
<td>Design Rules for the Well</td>
<td>52</td>
</tr>
<tr>
<td>SEM Views of Wells</td>
<td>54</td>
</tr>
</tbody>
</table>

**Chapter 3 The Metal Layers**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 The Bonding Pad</td>
<td>59</td>
</tr>
</tbody>
</table>
6.3 IV Characteristics of MOSFETs ................................. 144
   6.3.1 MOSFET Operation in the Triode Region 144
   6.3.2 The Saturation Region 146
       Cgs Calculation in the Saturation Region 148
6.4 SPICE Modeling of the MOSFET ............................... 149
   Model Parameters Related to $V_{THN}$ 149
   Long-Channel MOSFET Models 149
   Model Parameters Related to the Drain Current 150
   SPICE Modeling of the Source and Drain Implants 150
   Summary 151
   6.4.1 Some SPICE Simulation Examples 151
       Threshold Voltage and Body Effect 151
   6.4.2 The Subthreshold Current 152
6.5 Short-Channel MOSFETs ............................................. 154
   Hot Carriers 154
   Lightly Doped Drain (LDD) 155
6.5.1 MOSFET Scaling 155
   6.5.2 Short-Channel Effects 156
       Negative Bias Temperature Instability (NBTI) 156
       Oxide Breakdown 157
       Drain-Induced Barrier Lowering 157
       Gate-Induced Drain Leakage 157
       Gate Tunnel Current 157
6.5.3 SPICE Models for Our Short-Channel CMOS 157
   Process
       BSIM4 Model Listing (NMOS) 157
       BSIM4 Model Listing (PMOS) 159
   Simulation Results 160

Chapter 7 CMOS Fabrication by Jeff Jessing 165

7.1 CMOS Unit Processes .............................................. 165
   7.1.1 Wafer Manufacture 165
       Metallurgical Grade Silicon (MGS) 166
       Electronic Grade Silicon (EGS) 166
       Czochralski (CZ) Growth and Wafer Formation 166
   7.1.2 Thermal Oxidation 167
   7.1.3 Doping Processes 168
       Ion Implantation 169
Solid State Diffusion 170

7.1.4 Photolithography 170
   Resolution 172
   Depth of Focus 173
   Aligning Masks 173

7.1.5 Thin Film Removal 173
   Thin Film Etching 174
   Wet Etching 174
   Dry Etching 175
   Chemical Mechanical Polishing 176

7.1.6 Thin Film Deposition 177
   Physical Vapor Deposition (PVD) 178
   Chemical Vapor Deposition (CVD) 179

7.2 CMOS Process Integration .................................. 180
   FEOL 181
   BEOL 181
   CMOS Process Description 181

7.2.1 Frontend-of-the-Line Integration 182
   Starting Material 182
   Shallow Trench Isolation Module 184
   Twin Tub Module 188
   Gate Module 192
   Source/Drain Module 194

7.2.2 Backend-of-the-Line Integration 196
   Self-Aligned Silicide (Salicide) Module 197
   Pre-Metal Dielectric 199
   Contact Module 200
   Metallization 1 202
   Intra-Metal Dielectric 1 Deposition 204
   Via 1 Module 205
   Metallization 2 205
   Additional Metal/Dielectric Layers 206
   Final Passivation 209

7.3 Backend Processes ........................................ 210
   Wafer Probe 210
   Die Separation 212
   Packaging 212
   Final Test and Burn-In 212

7.4 Advanced CMOS Process Integration 212
9.1.1 The Square-Law Equations 279
  PMOS Square-Law Equations 280
  Qualitative Discussion 280
  Threshold Voltage and Body Effect 283
  Qualitative Discussion 284
  The Triode Region 285
  The Cutoff and Subthreshold Regions 286
9.1.2 Small Signal Models 286
  Transconductance 287
  AC Analysis 292
  Transient Analysis 293
  Body Effect Transconductance, \(g_{mb}\) 294
  Output Resistance 295
  MOSFET Transition Frequency, \(f_T\) 297
  General Device Sizes for Analog Design 298
  Subthreshold \(g_m\) and \(V_{THN}\) 299
9.1.3 Temperature Effects 300
  Threshold Variation and Temperature 300
  Mobility Variation with Temperature 301
  Drain Current Change with Temperature 302
9.2 Short-Channel MOSFETs 302
  9.2.1 General Design (A Starting Point) 303
    Output Resistance 304
    Forward Transconductance 304
    Transition Frequency 305
  9.2.2 Specific Design (A Discussion) 306
9.3 MOSFET Noise Modeling 308
  Drain Current Noise Model 308

Chapter 10 Models for Digital Design 327
  Miller Capacitance 327
  10.1 The Digital MOSFET Model 328
    Effective Switching Resistance 328
    Short-Channel MOSFET Effective Switching Resistance 330
    10.1.1 Capacitive Effects 331
    10.1.2 Process Characteristic Time Constant 331
    10.1.3 Delay and Transition Times 333
    10.1.4 General Digital Design 326
  10.2 The MOSFET Pass Gate 326
### Chapter 13 Clocked Circuits

13.1 The CMOS TG ........................................ 389  
   Series Connection of TGs 390  
13.2 Applications of the Transmission Gate  ................. 391  
   Path Selector 391  
   Static Circuits 394  
13.3 Latches and Flip-Flops  ........................................ 395  
   Basic Latches 395  
   An Arbiter 396  
   Flip-Flops and Flow-through Latches 397  
   An Edge-Triggered D-FF 399  
   Flip-Flop Timing 400  
13.4 Examples ............................................. 402  

### Chapter 14 Dynamic Logic Gates

14.1 Fundamentals of Dynamic Logic  ....................... 411  
   14.1.1 Charge Leakage 411  
   14.1.2 Simulating Dynamic Circuits 414  
   14.1.3 Nonoverlapping Clock Generation 415  
   14.1.4 CMOS TG in Dynamic Circuits 416  
14.2 Clocked CMOS Logic .................................. 417  
   Clocked CMOS Latch 417  
   An Important Note 417  
   PE Logic 418  
   Domino Logic 419  
   NP Logic (Zipper Logic) 420  
   Pipelining 421  

### Chapter 15 CMOS Layout Examples

15.1 Chip Layout ............................................ 426  
   Regularity 426  
   Standard Cell Examples 426  
   Power and Ground Considerations 428  
   An Adder Example 431  
   A 4-to-1 MUX/DEMUX 433  
15.2 Layout Steps by Dean Moriarty  ...................... 434  
   Planning and Stick Diagrams 434  
   Device Placement 437  
   Polish 437  
   Standard Cells Versus Full-Custom Layout 437
Chapter 16 Memory Circuits

16.1 Array Architectures ........................................ 446
   16.1.1 Sensing Basics ........................................ 446
      NMOS Sense Amplifier (NSA) .................. 447
      The Open Array Architecture ................ 447
      PMOS Sense Amplifier (PSA) .................. 450
      Refresh Operation .................................... 452
   16.1.2 The Folded Array ..................................... 452
      Layout of the DRAM Memory Bit (Mbit) ........ 453
   16.1.3 Chip Organization ................................... 458

16.2 Peripheral Circuits ......................................... 458
   16.2.1 Sense Amplifier Design ............................. 458
      Kickback Noise and Clock Feedthrough ........ 459
      Memory ............................................... 461
      Current Draw ....................................... 461
      Contention Current (Switching Current) ...... 461
      Removing Sense Amplifier Memory ............ 462
      Creating an Imbalance and Reducing Kickback Noise 462
      Increasing the Input Range ..................... 465
      Simulation Examples ................................. 466
   16.2.2 Row/Column Decoders ................................ 467
      Global and Local Decoders ....................... 468
      Reducing Decoder Layout Area .................. 470
   16.2.3 Row Drivers ......................................... 470

16.3 Memory Cells .................................................. 471
   16.3.1 The SRAM Cell ...................................... 473
   16.3.2 Read-Only Memory (ROM) ........................... 473
   16.3.3 Floating Gate Memory ............................. 473
      The Threshold Voltage ............................. 474
      Erasable Programmable Read-Only Memory ...... 477
      Two Important Notes ............................... 478
      Flash Memory ....................................... 479

Chapter 17 Sensing Using $\Delta \Sigma$ Modulation

17.1 Qualitative Discussion .................................. 494
   17.1.1 Examples of DSM .................................. 494
      The Counter ......................................... 495
      Cup Size ........................................... 496
      Another Example .................................. 496
   17.1.2 Using DSM for Sensing in Flash Memory ....... 496
### Chapter 18 Special Purpose CMOS Circuits

#### 18.1 The Schmitt Trigger
- 18.1.1 Design of the Schmitt Trigger
- Switching Characteristics
- 18.1.2 Applications of the Schmitt Trigger

#### 18.2 Multivibrator Circuits
- 18.2.1 The Monostable Multivibrator
- 18.2.2 The Astable Multivibrator

#### 18.3 Input Buffers
- 18.3.1 Basic Circuits
- Skew in Logic Gates
- 18.3.2 Differential Circuits
- Transient Response
- 18.3.3 DC Reference
- 18.3.4 Reducing Buffer Input Resistance

#### 18.4 Charge Pumps (Voltage Generators)
- Negative Voltages
- Using MOSFETs for the Capacitors
- 18.4.1 Increasing the Output Voltage
- 18.4.2 Generating Higher Voltages: The Dickson Charge Pump
- Clock Driver with a Pumped Output Voltage
- NMOS Clock Driver
- 18.4.3 Example
### Chapter 19 Digital Phase-Locked Loops

19.1 The Phase Detector ........................................ 563
   19.1.1 The XOR Phase Detector 563
   19.1.2 The Phase Frequency Detector 567
19.2 The Voltage-Controlled Oscillator .......................... 570
   19.2.1 The Current-Starved VCO 570
      Linearizing the VCO's Gain 573
   19.2.2 Source-Coupled VCOs 574
19.3 The Loop Filter ........................................... 576
   19.3.1 XOR DPLL 577
      Active-PI Loop Filter 581
   19.3.2 PFD DPLL 583
      Tri-State Output 583
      Implementing the PFD in CMOS 584
      PFD with a Charge Pump Output 587
      Practical Implementation of the Charge Pump 588
      Discussion 589
19.4 System Concerns ........................................... 590
   19.4.1 Clock Recovery from NRZ Data 593
      The Hogge Phase Detector 596
      Jitter 598
19.5 Delay-Locked Loops ........................................ 600
   Delay Elements 602
   Practical VCO and VCDL Design 602
19.6 Some Examples ............................................ 603
   19.6.1 A 2 GHz DLL 603
   19.6.2 A 1 Gbit/s Clock-Recovery Circuit 609

### Chapter 20 Current Mirrors

20.1 The Basic Current Mirror .................................. 621
   20.1.1 Long-Channel Design 622
   20.1.2 Matching Currents in the Mirror 624
      Threshold Voltage Mismatch 624
      Transconductance Parameter Mismatch 624
      Drain-to-Source Voltage and Lambda 625
      Layout Techniques to Improve Matching 625
      Layout of the Mirror with Different Widths 627
   20.1.3 Biasing the Current Mirror 628
      Using a MOSFET-Only Reference Circuit 629
      Supply Independent Biasing 631
Small-Signal Gain 686
Open Circuit Gain 686
High-Impedance and Low-Impedance Nodes 687
Frequency Response 687
Pole Splitting 689
Pole Splitting Summary 692
Canceling the RHP Zero 697
Noise Performance of the CS Amplifier with Current Source Load 698

21.2.2 The Cascode Amplifier 698
Frequency Response 699
Class A Operation 700
Noise Performance of the Cascode Amplifier 700
Operation as a Transimpedance Amplifier 701

21.2.3 The Common-Gate Amplifier 702
21.2.4 The Source Follower (Common-Drain Amplifier) 702
Body Effect and Gain 703
Level Shifting 704
Input Capacitance 705
Noise Performance of the SF Amplifier 706
Frequency Behavior 706
SF as an Output Buffer 708
A Class AB Output Buffer Using SFs 709

21.3 The Push-Pull Amplifier 710
21.3.1 DC Operation and Biasing 711
Power Conversion Efficiency 711
21.3.2 Small-Signal Analysis 714
21.3.3 Distortion 716
Modeling Distortion with SPICE 717

Chapter 22 Differential Amplifiers 735
22.1 The Source-Coupled Pair 735
22.1.1 DC Operation 735
Maximum and Minimum Differential Input Voltage 736
Maximum and Minimum Common-Mode Input Voltage 737
Current Mirror Load 739
Biasing from the Current Mirror Load 740
Minimum Power Supply Voltage 741
22.1.2 AC Operation 741
Low-Frequency, Open Loop Gain, $A_{OLDC}$ 804
Input Common-Mode Range 804
Power Dissipation 805
Output Swing and Current Source/Sinking Capability 805
Offsets 805
Compensating the Op-Amp 806
Gain and Phase Margins 810
Removing the Zero 811
Compensation for High-Speed Operation 812
Slew-Rate Limitations 816
Common-Mode Rejection Ratio (CMRR) 818
Power Supply Rejection Ratio (PSRR) 819
Increasing the Input Common-Mode Voltage Range 820
Estimating Bandwidth in Op-Amps Circuits 821
24.2 An Op-Amp with Output Buffer ........................ 822
Compensating the Op-Amp 822
24.3 The Operational Transconductance Amplifier (OTA) ........... 824
Unity-Gain Frequency, $f_{un}$ 825
Increasing the OTA Output Resistance 826
An Important Note 827
OTA with an Output Buffer (An Op-Amp) 828
The Folded-Cascode OTA and Op-Amp 830
24.4 Gain-Enhancement ................................... 835
Bandwidth of the Added GE Amplifiers 837
Compensating the Added GE Amplifiers 838
24.5 Some Examples and Discussions .......................... 839
A Voltage Regulator 839
Bad Output Stage Design 844
Three-Stage Op-Amp Design 846
Chapter 25 Dynamic Analog Circuits 857
25.1 The MOSFET Switch .................................... 857
Charge Injection 858
Capacitive Feedthrough 859
Reduction of Charge Injection and Clock Feedthrough 860
$kT/C$ Noise 861
25.1.1 Sample-and-Hold Circuits 861
25.2 Fully-Differential Circuits ................................ 864
Gain 864
Common-Mode Feedback 864
Coupled Noise Rejection 865
Other Benefits of Fully-Differential Op-Amps 865
25.2.1 A Fully-Differential Sample-and-Hold 866
Connecting the Inputs to the Bottom (Poly1) Plate 867
Bottom Plate Sampling 868
SPICE Simulation 868
25.3 Switched-Capacitor Circuits ........................... 869
25.3.1 Switched-Capacitor Integrator 871
Parasitic Insensitive 872
Other Integrator Configurations 872
Exact Frequency Response of a Switched-Capacitor Integrator 876
Capacitor Layout 877
Op-Amp Settling Time 878
25.4 Circuits ....................................................... 879
Reducing Offset Voltage of an Op-Amp 879
Dynamic Comparator 880
Dynamic Current Mirrors 882
Dynamic Amplifiers 884
Chapter 26 Operational Amplifiers II 889
26.1 Biasing for Power and Speed ............................. 889
26.1.1 Device Characteristics 890
26.1.2 Biasing Circuit 891
Layout of Differential Op-Amps 891
Self-Biased Reference 891
26.2 Basic Concepts ............................................ 892
Modeling Offset 892
A Diff-Amp 893
A Single Bias Input Diff-Amp 894
The Diff-Amp's Tail Current Source 895
Using a CMFB Amplifier 895
Compensating the CMFB Loop 896
Extending the CMFB Amplifier Input Range 898
Dynamic CMFB 899
26.3 Basic Op-Amp Design ..................................... 900
The Differential Amplifier 902
Adding a Second Stage (Making an Op-Amp) 903
Step Response 904
Adding CMFB 905
CMFB Amplifier
The Two-Stage Op-Amp with CMFB
Origin of the Problem
Simulation Results
Using MOSFETs Operating in the Triode Region
Start-up Problems
Lowering Input Capacitance
Making the Op-Amp More Practical
Increasing the Op-Amp’s Open-Loop Gain
Offsets
Op-Amp Offset Effects on Outputs
Single-Ended to Differential Conversion
CMFB Settling Time
CMFB in the Output Buffer (Fig. 26.43) or the Diff-Amp (Fig. 26.40)?
26.4 Op-Amp Design Using Switched-Capacitor CMFB
Clock Signals
Switched-Capacitor CMFB
The Op-Amp’s First Stage
The Output Buffer
An Application of the Op-Amp
Simulation Results
A Final Note Concerning Biasing

27.1 Basic CMOS Comparator Design
Preamplification
Decision Circuit
Output Buffer

27.1.1 Characterizing the Comparator
Comparator DC Performance
Transient Response
Propagation Delay
Minimum Input Slew Rate

27.1.2 Clocked Comparators
27.1.3 Input Buffers Revisited

27.2 Adaptive Biasing

27.3 Analog Multipliers

27.3.1 The Multiplying Quad
Simulating the Operation of the Multiplier
### Chapter 28 Data Converter Fundamentals by Harry Li

**28.1 Analog Versus Discrete Time Signals** .................................. 955
**28.2 Converting Analog Signals to Digital Signals** ................... 956
**28.3 Sample-and-Hold (S/H) Characteristics** .............................. 959
  - Sample Mode 959
  - Hold Mode 960
  - Aperture Error 960
**28.4 Digital-to-Analog Converter (DAC) Specifications** ............. 961
  - Differential Nonlinearity 964
  - Integral Nonlinearity 966
  - Offset 968
  - Gain Error 969
  - Latency 969
  - Signal-to-Noise Ratio (SNR) 969
  - Dynamic Range 969
**28.5 Analog-to-Digital Converter (ADC) Specifications** ............. 970
  - Quantization Error 971
  - Differential Nonlinearity 972
  - Missing Codes 974
  - Integral Nonlinearity 974
  - Offset and Gain Error 975
  - Aliasing 976
  - Signal-to-Noise Ratio 978
  - Aperture Error 979
**28.6 Mixed-Signal Layout Issues** ........................................... 979
  - Floorplanning 980
  - Power Supply and Ground Issues 980
  - Fully Differential Design 982
  - Guard Rings 982
  - Shielding 983
  - Other Interconnect Considerations 984

### Chapter 29 Data Converter Architectures by Harry Li

**29.1 DAC Architectures** .................................................... 987
  **29.1.1 Digital Input Code** ............................................ 987
  **29.1.2 Resistor String** ............................................. 987
    - Mismatch Errors Related to the Resistor-String DAC 990
    - Integral Nonlinearity of the Resistor-String DAC 991
## Differential Nonlinearity of the Worst-Case Resistor-String DAC

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.1.3 R-2R Ladder Networks</td>
<td>992</td>
</tr>
<tr>
<td>29.1.4 Current Steering</td>
<td>995</td>
</tr>
<tr>
<td>Mismatch Errors Related to Current-Steering DACs</td>
<td>997</td>
</tr>
<tr>
<td>29.1.5 Charge-Scaling DACs</td>
<td>999</td>
</tr>
<tr>
<td>Layout Considerations for a Binary-Weighted Capacitor Array</td>
<td>1001</td>
</tr>
<tr>
<td>The Split Array</td>
<td>1002</td>
</tr>
<tr>
<td>29.1.6 Cyclic DAC</td>
<td>1003</td>
</tr>
<tr>
<td>29.1.7 Pipeline DAC</td>
<td>1005</td>
</tr>
</tbody>
</table>

## Layout Considerations for a Binary-Weighted Capacitor Array

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.2 ADC Architectures</td>
<td>1006</td>
</tr>
<tr>
<td>29.2.1 Flash</td>
<td>1006</td>
</tr>
<tr>
<td>Accuracy Issues for the Flash ADC</td>
<td>1007</td>
</tr>
<tr>
<td>29.2.2 The Two-Step Flash ADC</td>
<td>1010</td>
</tr>
<tr>
<td>Accuracy Issues Related to the Two-Step Flash Converter</td>
<td>1012</td>
</tr>
<tr>
<td>Accuracy Issues Related to Operational Amplifiers</td>
<td>1013</td>
</tr>
<tr>
<td>29.2.3 The Pipeline ADC</td>
<td>1014</td>
</tr>
<tr>
<td>Accuracy Issues Related to the Pipeline Converter</td>
<td>1016</td>
</tr>
<tr>
<td>29.2.4 Integrating ADCs</td>
<td>1018</td>
</tr>
<tr>
<td>Single-Slope Architecture</td>
<td>1018</td>
</tr>
<tr>
<td>Accuracy Issues Related to the Single-Slope ADC</td>
<td>1020</td>
</tr>
<tr>
<td>Dual-Slope Architecture</td>
<td>1020</td>
</tr>
<tr>
<td>Accuracy Issues Related to the Dual-Slope ADC</td>
<td>1022</td>
</tr>
<tr>
<td>29.2.5 The Successive Approximation ADC</td>
<td>1022</td>
</tr>
<tr>
<td>The Charge-Redistribution Successive Approximation ADC</td>
<td>1025</td>
</tr>
<tr>
<td>Accuracy Issues Related to the Charge-Redistribution, Successive-Apoximation ADC</td>
<td>1026</td>
</tr>
<tr>
<td>29.2.6 The Oversampling ADC</td>
<td>1027</td>
</tr>
<tr>
<td>Differences in Nyquist Rate and Oversampled ADCs</td>
<td>1027</td>
</tr>
<tr>
<td>The First-Order ΣΔ Modulator</td>
<td>1029</td>
</tr>
<tr>
<td>The Higher Order ΣΔ Modulators</td>
<td>1033</td>
</tr>
</tbody>
</table>

## Chapter 30 Implementing Data Converters

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.1 R-2R Topologies for DACs</td>
<td>1043</td>
</tr>
<tr>
<td>30.1.1 The Current-Mode R-2R DAC</td>
<td>1044</td>
</tr>
<tr>
<td>30.1.2 The Voltage-Mode R-2R DAC</td>
<td>1045</td>
</tr>
<tr>
<td>30.1.3 A Wide-Swing Current-Mode R-2R DAC</td>
<td>1047</td>
</tr>
<tr>
<td>DNL Analysis</td>
<td>1048</td>
</tr>
</tbody>
</table>
31.2.2 Bandwidth Extension 1117
31.2.3 Reduction in Nonlinear Distortion 1118
31.2.4 Input and Output Impedance Control 1120
31.3 Recognizing Feedback Topologies ..................... 1120
   31.3.1 Input Mixing 1121
   31.3.2 Output Sampling 1121
   31.3.3 The Feedback Network 1122
      An Important Assumption 1123
      Counting Inversions Around the Loop 1124
      Examples of Recognizing Feedback Topologies 1124
   31.3.4 Calculating Open-Loop Parameters 1125
   31.3.5 Calculating Closed-Loop Parameters 1127
31.4 The Voltage Amp (Series-Shunt Feedback) ............... 1128
31.5 The Transimpedance Amp (Shunt-Shunt Feedback) ........ 1134
   31.5.1 Simple Feedback Using a Gate-Drain Resistor 1140
31.6 The Transconductance Amp (Series-Series Feedback) .... 1142
31.7 The Current Amplifier (Shunt-Series Feedback) .......... 1146
31.8 Stability .............................................. 1148
   31.8.1 The Return Ratio 1151
31.9 Design Examples ....................................... 1154
   31.9.1 Voltage Amplifiers 1154
      Amplifiers with Gain 1156
   31.9.2 A Transimpedance Amplifier 1158

Chapter 32 Hysteretic Power Converters 1175
32.1 A Review of Power and Energy Basics ..................... 1176
   An Analogy 1177
   32.1.1 Energy Storage in Inductors and Capacitors 1177
      Energy Storage in an Inductor 1178
      Energy Storage in a Capacitor 1178
32.1.2 Energy Use in Transmitting Data 1180
32.1.3 Selection and use of Switches 1181
   Using an NMOS Pull-Up 1183
   Effective Digital Resistance, A Comment 1184
   Driver Optimization 1184
   Higher Voltage Switches 1184
32.2 Switching Power Supplies: Some Examples ............... 1189
   32.2.1 The Buck SPS 1189
      Selecting the Inductor 1191
      Selecting the Capacitor 1191
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Supply Efficiency</td>
<td>1195</td>
</tr>
<tr>
<td>32.2.2 The Boost SPS</td>
<td>1196</td>
</tr>
<tr>
<td>Selecting the Inductor</td>
<td>1197</td>
</tr>
<tr>
<td>Selecting the Capacitor</td>
<td>1197</td>
</tr>
<tr>
<td>32.2.3 The Flyback SPS</td>
<td>1200</td>
</tr>
<tr>
<td>Quick Review of Transformers</td>
<td>1200</td>
</tr>
<tr>
<td>Operation of the Flyback SPS</td>
<td>1201</td>
</tr>
<tr>
<td>32.2.4 Pulse Width Modulation: A Control Loop Example</td>
<td>1204</td>
</tr>
<tr>
<td>Buck SPS Control Loop</td>
<td>1206</td>
</tr>
<tr>
<td>Boost SPS Control Loop</td>
<td>1207</td>
</tr>
<tr>
<td>Flyback SPS Control Loop</td>
<td>1208</td>
</tr>
<tr>
<td>Effective Series Resistance</td>
<td>1209</td>
</tr>
<tr>
<td>Some Comments</td>
<td>1210</td>
</tr>
<tr>
<td>32.3 Hysteretic Control</td>
<td>1210</td>
</tr>
<tr>
<td>32.3.1 Topologies</td>
<td>1211</td>
</tr>
<tr>
<td>32.3.2 Examples</td>
<td>1212</td>
</tr>
<tr>
<td>Buck HPS Control Loop</td>
<td>1212</td>
</tr>
<tr>
<td>Boost HPS Control Loop</td>
<td>1213</td>
</tr>
<tr>
<td>Flyback HPS Control Loop</td>
<td>1214</td>
</tr>
<tr>
<td>Some Final Comments</td>
<td>1216</td>
</tr>
<tr>
<td>Index</td>
<td>1219</td>
</tr>
<tr>
<td>About the Author</td>
<td>1235</td>
</tr>
</tbody>
</table>