Ultra Low Power Bioelectronics

Fundamentals, Biomedical Applications, and Bio-inspired Systems

RAHUL SARPESHKAR
Massachusetts Institute of Technology

CAMBRIDGE
UNIVERSITY PRESS

Contents

Acknowledgements *page xvi*

Section 1 Foundations 1

1 **The big picture** 3

1.1 Importance of ultra-low-power electronics 5
1.2 The power-efficient subthreshold regime of transistor Operation 7
1.3 Information, energy, and power 9
1.4 The Optimum point for digitization in a mixed-signal system 10
1.5 Examples of biomedical application contexts 14
1.6 Principles for ultra-low-power design 17
1.7 Ultra-low-power information processing in biology 18
1.8 Neuromorphic system example: the RF cochlea 19
1.9 Cytomorphic electronics 22
1.10 Energy sources 23
1.11 An overview of the book's chapters and organization 24
1.12 Some final notes 26

2 **Feedback systems: fundamentals, benefits, and root-locus analysis** 28

2.1 Feedback is universal 29
2.2 The basic linear feedback loop 32
2.3 Connections between feedback loops and circuits 35
2.4 The seven benefits of feedback 36
2.5 Root-locus techniques 44
2.6 Eight root-locus rules 46
2.7 Example of a root-locus plot 53
2.8 The zeros of a closed-loop system 55
2.9 Farewell to feedback systems 55

3 **MOS device physics: general treatment** 57

3.1 Intuitive description of MOS transistor Operation 60
3.2 Intuitive model of MOS transistor Operation 63

3.3 Intuitive energy viewpoint for MOS transistor operation 65
3.4 The MOS capacitor (MOSCAP) 68
3.5 Quantitative discussion of the MOSCAP 71
3.6 Determining $(Q_I + Q_{dep})$ in a MOSCAP for a given t_{ifs} 73
3.7 Equating the gate charge and bulk charge 76
3.8 Quantitative discussion of the MOSFET 79
3.9 Summary of physical insights 82

4 MOS device physics: practical treatment 84

4.1 The κ approximation 85
4.2 Charge-based current models with the κ approximation 92
4.3 Derivation of current in weak inversion 93
4.4 Derivation of current in strong inversion 95
4.5 Source-referenced model for strong inversion 97
4.6 Moderate inversion 101

5 MOS device physics: small-signal operation 103

5.1 Weak-inversion small-signal models 104
5.2 Strong-inversion small-signal models 108
5.3 Small-signal capacitance models in strong inversion 113
5.4 Extrinsic or parasitic capacitances 120
5.5 Small-signal capacitance models in weak inversion 122
5.6 The transit time 123
5.7 The `beta' of an MOS transistor 125

6 Deep submicron effects in MOS transistors 129

6.1 The dimensionless EKV model 130
6.2 Velocity saturation 133
6.3 Drain induced barrier lowering (DIBL) 140
6.4 Vertical-field effects 143
6.5 Effect on the intuitive model 145
6.6 High-frequency transistor models 146
6.7 Ballistic transport 147
6.8 Transport in nanoscale MOSFETs 149
6.9 Tunneling 151
6.10 Scaling of transistors in the future 152

7 Noise in devices 155

7.1 The mathematics of noise 155
7.2 Noise in subthreshold MOS transistors 161
7.3 Noise in resistors 165
7.4 Unity between thermal noise and shot noise 167

7.5 Noise in above-threshold MOS transistors 168
7.6 Input-referred gate noise 169
7.7 1/f or flicker noise in MOS transistors 170
7.8 Some notes on 1 /f noise 173
7.9 Thermal noise in short-channel devices 176
7.10 Thermal noise in moderate inversion 179
7.11 Induced gate noise 181
7.12 Some caveats about noise 182

8 Noise in electrical and non-electrical circuits 184

8.1 Noise in an RC lowpass-filter circuit 185
8.2 A subthreshold photoreceptor circuit 187
8.3 The equipartition theorem 190
8.4 Noise in a subthreshold transconductance amplifier 193
8.5 Noise in general circuits 200
8.6 An ultra-low-noise MEMS capacitance sensor 201

9 Feedback systems 212

9.1 The Nyquist criterion for stability 212
9.2 Nyquist-based criteria for robustness: Gain margin and phase margin 216
9.3 Compensation techniques 219
9.4 The closed-loop two-pole T-and-Q rules for feedback systems 228
9.5 Conditional stability 229
9.6 Describing-function analysis of nonlinear feedback systems 231
9.7 Positive feedback 232
9.8 Feedback in small-signal circuits 233
9.9 The Take label' circuit-analysis trick 235
9.10 A circuit example 235

10 Return-ratio analysis 240

10.1 Return ratio for a dependent generator 241
10.2 Return ratio for a passive impedance 243
10.3 Transfer function modification with the return ratio 244
10.4 Robustness analysis with the return ratio 249
10.5 Examples of return-ratio analysis 250
10.6 Blackman's impedance formula 256
10.7 Driving-point transistor impedances with Blackman's formula 258
10.8 Middlebrook's extra-element theorem 261
10.9 Thevenin's theorem as a special case of return-ratio analysis 264

10.10 Two final examples of return-ratio analysis 265
10.11 Summary of key results 270

Section II Low-power analog and biomedical circuits 273

11 Low-power transimpedance amplifiers and photoreceptors 275

11.1 Transimpedance amplifiers 275
11.2 Phototransduction in silicon 278
11.3 A transimpedance-amplifier-based photoreceptor 283
11.4 Feedback analysis of photoreceptor 286
11.5 Noise analysis of photoreceptor 292
11.6 The adaptation resistor *RA* 294
11.7 Experimental measurements of the photoreceptor 296
11.8 Adaptive biasing of *1A* for energy efficiency 297
11.9 Zeros in the feedback path 298

12 Low-power transconductance amplifiers and scaling laws for power in analog circuits 301

12.1 A simple ordinary transconductance amplifier (OTA) 302
12.2 A low-power wide-linear-range transconductance amplifier: the big picture 303
12.3 WLR small-signal and linear-range analysis 305
12.4 WLR dc characteristics 310
12.5 Dynamic characteristics of the WLR 317
12.6 Noise analysis 317
12.7 Distortion analysis 322
12.8 Signal-to-noise ratio and power analysis 323
12.9 Scaling laws for power in analog circuits 325
12.10 Low-voltage transconductance amplifiers and low-voltage analog design 326
12.11 Robust Operation of subthreshold circuits 329

13 Low-power filters and resonators 330

13.1 G„„—C filter synthesis 331
13.2 Gyrators 333
13.3 Introduction to second-order systems 334
13.4 Synthesis of a second-order *G ni—C* filter 337
13.5 Analysis of a second-order *Gni—C* filter 339
13.6 Synthesis and analysis of an alternative *Gm—C* filter 342
13.7 Higher-order *Gm C* filter design 347
13.8 A —s2-plane geometry for analyzing the frequency response of linear systems 347

14 Low-power current-mode circuits 354

14.1 Voltage versus current 355
14.2 Static translinear circuits 356
14.3 Dynamic translinear lowpass filters 359
14.4 Dynamic translinear integrators and high-order filters 365
14.5 Biasing of current-mode filters 367
14.6 Noise, SNR, and dynamic range of log-domain filters 370
14.7 Log-domain vs. *Gni-C* filters 372
14.8 Winner-take-all circuits 373
14.9 Large-signal Operation of the winner-take-all circuit 379
14.10 Distributed-feedback circuits 380

15 Ultra-low-power and neuron-inspired analog-to-digital conversion for biomedical systems 385

15.1 Review of ADC topologies 389
15.2 A neuron-inspired ADC for biomedical applications 395
15.3 Computational ADCs and time-to-digital ADCs 408
15.4 A time-based EA ADC 410
15.5 Pipelined ADCs with comparators 411
15.6 Adiabatic charging and energy-efficient comparators in ADCs 412
15.7 Digital correction of analog errors 415
15.8 Neurons and ADCs 416

Section III Low-power RF and energy-harvesting circuits for biomedical systems 419

16 Wireless inductive power links for medical implants 421

16.1 Theory of linear inductive links 422
16.2 Experimental system design 441
16.3 Experimental measurements 448

17 Energy-harvesting RF antenna power links 454

17.1 Intuitive understanding of Maxwell's equations 455
17.2 The non-lossy, one-dimensional transmission line 456
17.3 The impedance of free space 459
17.4 Thevenin-equivalent circuit models of antennas 459
17.5 Near-field coupling 463
17.6 Far-field coupling: the `monopole' antenna 463
17.7 Far-field coupling: basics of dipole antennas 465
17.8 Directional radiation and antenna gain 467
17.9 Derivation of far-field transfer impedance or z_{12} 469
17.10 Impedance matching: the Bode-Fano criterion 471
17.11 Making the antenna and the load part of the matching network 474

17.12 Rectifier basics 477
17.13 Rectifier analysis and optimization 481
17.14 Output voltage ripple in rectifiers 482
17.15 Latchup in CMOS rectifiers 483
17.16 Rectifier modeling 483
17.17 Experimental measurements 486
17.18 Summary 488

18 Low-power RF telemetry in biomedical implants 489

18.1 Impedance modulation in coupled parallel resonators 493
18.2 Impedance-modulation transceiver 495
18.3 Pulse-width modulation receiver 503
18.4 Dynamic effects in impedance modulation 505
18.5 Experimental results for a complete transceiver 508
18.6 Energy efficiency of the uplink and downlink 511
18.7 Scaling laws for power consumption in impedance-modulation links 511
18.8 The energy per bit in impedance-modulation links 518
18.9 Incoherent versus coherent RF receivers 522
18.10 Radiated emissions and FCC regulations 523
18.11 Seven considerations in choosing a carrier frequency 524
18.12 RF antenna links for implants 525
18.13 The skin depth of biological tissue 525

Section IV Biomedical electronic systems 529

19 Ultra-low-power implantable medical electronics 531

19.1 Cochlear implants or bionic ears 534
19.2 An ultra-low-power programmable analog bionic ear processor 537
19.3 Low-power electrode stimulation 558
19.4 Highly miniature electrode-stimulation circuits 562
19.5 Brain-machine interfaces for the blind 565
19.6 Brain-machine interfaces for paralysis, speech, and other disorders 572
19.7 Summary 575

20 Ultra_low_power noninvasive medical electronics 579

20.1 Analog integrated-circuit switched-capacitor model of the heart 581
20.2 The electrocardiogram 585
20.3 A micropower electrocardiogram amplifier 590
20.4 Low-power pulse oximetry 595
20.5 Battery-free tags for body sensor networks 601

20.6 Intra-body galvanic communication networks 604
20.7 Biomolecular sensing 605

Section V Principles for ultra-low-power analog and digital design 615

21 Principles for ultra-low-power digital design 617

21.1 Subthreshold CMOS-inverter basics 618
21.2 Sizing and topologies for robust subthreshold Operation 622
21.3 Types of power dissipation in digital circuits 623
21.4 Energy efficiency in digital systems 630
21.5 Optimization of energy efficiency in the subthreshold regime 632
21.6 Optimization of energy efficiency in all regimes of Operation 635
21.7 Varying the power-supply voltage and threshold voltage 641
21.8 Gated clocks 641
21.9 Basics of adiabatic computing 642
21.10 Adiabatic clocks 645
21.11 Architectures and algorithms for improving energy efficiency 647

22 Principles for ultra_low_power analog and mixed_signal design 651

22.1 Power consumption in analog and digital systems 653
22.2 The low-power hand 661
22.3 The Optimum point for digitization in a mixed-signal system 663
22.4 Common themes in low-power analog and digital design 669
22.5 The Shannon limit for energy efficiency 671
22.6 Collective analog or hybrid computation 674
22.7 HSMs: general-purpose mixed-signal systems with feedback 679
22.8 General principles for low-power mixed-signal system design 683
22.9 The evolution of low-power design 691
22.10 Sensors and actuators 692

Section VI Bio-inspired systems 695

23 Neuromorphic electronics 697

23.1 Transmission-line theory 705
23.2 The cochlea: biology, motivations, theory, and RF-eochlea design 706
23.3 Integrated-circuit unidirectional and bidirectional RF cochleas 721
23.4 Audio cochleas and bio-inspired noise-robust spectral analysis 725
23.5 A bio-inspired analog vocal tract 728
23.6 Bio-inspired vision architectures 733
23.7 Hybrid analog-digital computation in the brain 739
23.8 Spike-based hybrid computers 741
23.9 Collective analog or hybrid systems 743

23.10 Energy efficiency in neurobiological systems 743
23.11 Other work 747
23.12 Appendix: Power and computation in the brain, eye, ear, and body 747

24 Cytomorphic electronics: cell-inspired electronics for systems and synthetic biology 753

24.1 Electronic analogies of chemical reactions 755
24.2 Log-domain current-mode models of chemical reactions and protein-protein networks 759
24.3 Analog circuit models of gene-protein dynamics 766
24.4 Logic-like operations in gene-protein circuits 769
24.5 Stochastics in DNA-protein circuits 772
24.6 An example of a simple DNA-protein circuit 774
24.7 Circuits-and-feedback techniques for systems and synthetic biology 776
24.8 Hybrid analog-digital computation in cells and neurons 783

Section VII Energy sources 787

25 Batteries and electrochemistry 789

25.1 Basic Operation of a battery 789
25.2 Example mechanism for battery Operation 791
25.3 Chemical reaction kinetics and electrode current 793
25.4 Mass-transport limitations 796
25.5 Large-signal equivalent circuit of a battery 799
25.6 Battery voltage degradation with decreasing state of charge 802
25.7 Small-signal equivalent circuit of a battery and of electrodes 806
25.8 Operation of a lithium-ion battery 812
25.9 Operation of a zinc-air battery 815
25.10 Basic Operation of fuel cells 816
25.11 Energy density, power density, and system cost 817

26 Energy harvesting and the future of energy 822

26.1 Sources of energy 824
26.2 Electrical circuit models of mechanical systems 825
26.3 Energy harvesting of body motion 827
26.4 Energy harvesting of body heat 831
26.5 Power consumption of the world 835
26.6 A circuit model for car power consumption 836
26.7 Electric cars versus gasoline cars 841
26.8 Cars versus animals 844
26.9 Principles of low-power design in transportation 846

26.10 Solar electricity generation 848
26.11 Biofuels 854
26.12 Energy use and energy generation 855

Epilogue 859
Bibliography 860
Index 879