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978-0-521-11036-5 - CMOS Analog Design Using All-Region MOSFET Modeling

Marcio Cherem Schneider and Carlos Galup-Montoro

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CMOS Analog Design Using All-Region MOSFET Modeling

Covering the essentials of analog circuit design, this book takes a unique design approach based on a MOSFET model valid for all operating regions, rather than the standard square-law model. Opening chapters focus on device modeling, integrated circuit technology, and layout, whilst later chapters go on to cover noise and mismatch, and analysis and design of the basic building blocks of analog circuits, such as current mirrors, voltage references, voltage amplifiers, and operational amplifiers. An introduction to continuous-time filters is also provided, as are the basic principles of sampled-data circuits, especially switched-capacitor circuits. The final chapter then reviews MOSFET models and describes techniques to extract design parameters. With numerous design examples and exercises also included, this is ideal for students taking analog CMOS design courses and also for circuit designers who need to shorten the design cycle.

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AND
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[More information](#)

To our wives Rita and Marlene

Contents

<i>Preface</i>	<i>page xv</i>
1 Introduction to analog CMOS design	1
1.1 Analog design	1
1.1.1 The need for analog design	1
1.1.2 Tradeoffs in analog design	2
1.1.3 The importance of component modeling	2
1.2 Bipolar and metal–oxide–semiconductor field-effect transistors	3
1.2.1 p–n Junctions	3
1.2.2 Bipolar junction transistors	5
1.2.3 MOS field-effect transistors	7
1.2.4 Important differences between BJTs and MOSFETs	14
1.3 Analog bipolar and MOS integrated circuits	16
1.3.1 Analysis and design of integrated circuits	16
1.3.2 Design of common-emitter and common-source amplifiers	17
Problems	21
References	24
2 Advanced MOS transistor modeling	26
2.1 Fundamentals of the MOSFET model	26
2.1.1 Electrons and holes in semiconductors	26
2.1.2 The two-terminal MOS structure	28
2.1.3 Accumulation, depletion, and inversion (for p-type substrates)	31
2.1.4 The small-signal equivalent circuit of the two-terminal MOS (for p-type substrates)	32
2.1.5 The three-terminal MOS structure and the unified charge-control model (UCCM)	34
2.1.6 The pinch-off voltage	38
2.1.7 The Pao–Sah exact I – V model	39
2.1.8 A charge-sheet formula for the current	41
2.1.9 A charge-control compact model	41
2.1.10 Threshold voltage	42

viii	Contents	
2.2	A design-oriented MOSFET model	45
2.2.1	Forward and reverse components of the drain current	45
2.2.2	Universal dc characteristics	48
2.2.3	MOSFET operation in weak and strong inversion	51
2.2.4	Small-signal transconductances	53
2.3	Dynamic MOSFET models	57
2.3.1	Stored charges	57
2.3.2	Capacitive coefficients	59
2.3.3	Capacitances of the extrinsic transistor	62
2.3.4	A non-quasi-static small-signal model	62
2.3.5	A quasi-static small-signal model	65
2.3.6	The intrinsic transition frequency	67
2.4	Short-channel effects in MOSFETs	68
2.4.1	Effective mobility	68
2.4.2	Velocity saturation	69
2.4.3	Channel-length modulation	71
2.4.4	Drain-induced barrier lowering	72
2.4.5	Output conductance in saturation	73
2.4.6	Gate tunneling currents	75
2.4.7	Bulk current	76
A2.1	Semiconductor charges	77
A2.2	Drain- and source-associated inversion charges	79
A2.3	Summary of n-channel MOSFET equations: UCCM, current, charges, transconductances, and capacitances including short-channel effects	81
A2.4	An alternative low-frequency small-signal model of the MOSFET in saturation	81
	Problems	84
	References	86
3	CMOS technology, components, and layout techniques	88
3.1	An overview of CMOS technology	88
3.1.1	Basic process steps in monolithic IC fabrication	88
3.1.2	Generic deep-submicron CMOS process flow	89
3.1.3	Main parameters in 350-, 180-, and 90-nm processes	92
3.2	Devices in CMOS technology	93
3.2.1	Resistors	94
3.2.2	Capacitors	101
3.2.3	Inductors	109
3.2.4	Bipolar transistors	112
3.3	Latchup	114
3.4	Analog layout issues	115
3.4.1	Optical lithography	115

Contents		ix
	3.4.2 Mask layout and design rules	118
	3.4.3 MOSFET layout	121
	Problems	128
	References	130
4	Temporal and spatial fluctuations in MOSFETs	134
4.1	Types of noise	134
4.1.1	Thermal noise	134
4.1.2	Shot noise	136
4.1.3	Flicker noise	136
4.2	Modeling the drain-current fluctuations in MOSFETs	137
4.3	Thermal noise in MOSFETs	139
4.3.1	Channel thermal noise	139
4.3.2	Short-channel effects on channel thermal noise	140
4.3.3	Induced gate noise	141
4.4	Flicker noise in MOSFETs	144
4.5	Design-oriented noise models	147
4.5.1	Consistency of noise models	147
4.5.2	The thermal noise excess factor	147
4.5.3	Flicker noise in terms of inversion levels	148
4.5.4	The corner frequency	150
4.5.5	Two-port noise models	151
4.6	Systematic and random mismatch	154
4.6.1	Pelgrom’s model of mismatch	155
4.6.2	(Mis)matching energy	161
4.6.3	The number-fluctuation mismatch model	162
4.6.4	The dependence of mismatch on bias, dimensions, and technology	164
4.6.5	Matching analysis of analog circuits	167
	Problems	170
	References	175
5	Current mirrors	177
5.1	A simple MOS current mirror	177
5.1.1	The ideal current mirror	177
5.1.2	The two-transistor current mirror	177
5.1.3	Error caused by difference between drain voltages	179
5.1.4	Error caused by transistor mismatch	180
5.1.5	Small-signal characterization and frequency response	184
5.1.6	Noise	186
5.2	Cascode current mirrors	187
5.2.1	Self-biased cascode current mirrors	188
5.2.2	High-swing cascode current mirrors	189

x	Contents	
	5.3 Advanced current mirrors	191
	5.4 Class-AB current mirrors	192
	A5.1 Harmonic distortion	193
	Problems	195
	References	198
6	Current sources and voltage references	199
	6.1 A simple MOS current source	199
	6.2 The Widlar current source	200
	6.3 Self-biased current sources (SBCSs)	201
	6.4 A MOSFET-only self-biased current source	205
	6.5 Bandgap voltage references	208
	6.5.1 The operating principle of the bandgap reference	209
	6.5.2 CMOS bandgap references	210
	6.5.3 A CMOS bandgap reference with sub-1-V operation	214
	6.5.4 A resistorless CMOS bandgap reference	216
	6.6 CMOS voltage references based on weighted V_{GS}	217
	6.7 A current-calibrated CMOS PTAT voltage reference	218
	Problems	219
	References	222
7	Basic gain stages	225
	7.1 Common-source amplifiers	225
	7.1.1 Resistive load	225
	7.1.2 Diode-connected load	226
	7.1.3 The intrinsic gain stage	228
	7.1.4 Current source load	231
	7.1.5 The push–pull amplifier (static CMOS inverter)	236
	7.2 Common-gate amplifiers	239
	7.3 Source followers	242
	7.4 Cascode amplifiers	246
	7.4.1 Telescopic- and folded-cascode amplifiers	246
	7.4.2 The gain-boost technique	250
	7.5 Differential amplifiers	252
	7.5.1 The source-coupled pair	252
	7.5.2 Resistive-load differential amplifiers	259
	7.5.3 Current-mirror-load differential amplifiers	260
	7.6 Sizing and biasing of MOS transistors for amplifier design	278
	7.6.1 Sizing and biasing of a common-source amplifier	279
	7.6.2 The design procedure for a common-source amplifier	280
	7.6.3 MOSVIEW: a graphical interface for MOS transistor design	281

Contents	xi
7.7 Reuse of MOS analog design	283
7.7.1 Effects of scaling on analog circuits	284
7.7.2 Analog resizing rules	285
Problems	288
References	290
8 Operational amplifiers	292
8.1 Applications and performance parameters	292
8.1.1 The ideal operational amplifier	292
8.1.2 Basic applications of operational amplifiers	293
8.1.3 Performance parameters	297
8.2 The differential amplifier as an operational amplifier	299
8.2.1 The simple-stage differential amplifier	299
8.2.2 The telescopic-cascode differential amplifier	301
8.3 The symmetric operational amplifier	302
8.3.1 DC characteristics	302
8.3.2 Small-signal characteristics and noise	304
8.3.3 Slew rate	305
8.4 The folded-cascode operational amplifiers	306
8.4.1 DC characteristics	306
8.4.2 Small-signal characteristics and noise	308
8.4.3 Slew rate	312
8.5 Two-stage operational amplifiers	320
8.5.1 Cascade versus cascode amplifiers	320
8.5.2 DC characteristics of the two-stage amplifier	321
8.5.3 Small-signal characteristics of the two-stage Miller-compensated op amp	322
8.5.4 Slew rate	334
8.5.5 Alternative forms of compensation of the two-stage op amp	336
8.6 Three-stage operational amplifiers	339
8.7 Rail-to-rail input stages	340
8.8 Class-AB output stages for operational amplifiers	342
8.9 Fully-differential operational amplifiers	350
A8.1 Systematic offset of a two-stage op amp	359
Problems	360
References	363
9 Fundamentals of integrated continuous-time filters	366
9.1 Basics of MOSFET-C filters	366
9.1.1 The MOSFET as a tunable resistor	367
9.1.2 Balanced transconductors for MOSFET-C filters	368
9.1.3 MOSFET-C integrators	370
9.1.4 Filter examples	376

xii	Contents	
	9.2 Basics of OTA-C filters	378
	9.2.1 Transconductors	379
	9.2.2 G_m -C integrators	383
	9.2.3 Signal-to-noise ratio, dynamic range, and power	386
	9.2.4 Filter examples	390
	9.3 Digitally-programmable continuous-time filters	393
	9.4 On-chip tuning schemes	395
	A9.1 Distortion of the MOSFET operating as a resistor	397
	Problems	399
	References	400
10	Fundamentals of sampled-data circuits	404
	10.1 MOS sample-and-hold circuits	404
	10.1.1 Sample-and-hold basics	404
	10.1.2 Thermal noise	406
	10.1.3 Switch on-resistance	409
	10.1.4 Sampling distortion due to switch on-resistance	410
	10.1.5 Linearization of the MOS sampling switch	412
	10.1.6 Charge injection by the switch	413
	10.1.7 Low-voltage sample-and-hold circuits	417
	10.1.8 Jitter analysis	421
	10.1.9 Tradeoff between resolution and sampling rate in analog-to-digital converters	422
	10.2 Basics of switched-capacitor filters	423
	10.2.1 Basic principles of operation of switched-capacitor circuits	423
	10.2.2 Switched-capacitor integrators	426
	10.2.3 Offset compensation	429
	10.2.4 Biquad filters	430
	10.2.5 Amplifier specifications	433
	10.2.6 Low-distortion switched-capacitor filters	435
	10.3 Switched-capacitor circuits as charge processors	437
	10.3.1 Realization of linear voltage processors	438
	10.3.2 Implementation issues	440
	10.4 Alternative switched-circuit techniques	441
	A10.1 Modeling the sampling distortion due to the non-linearity of the switch on-resistance	444
	Problems	446
	References	450
11	Overview of MOSFET models and parameter extraction for design	452
	11.1 MOSFET models for circuit simulation	452
	11.1.1 Threshold-voltage-based models (BSIM3 and BSIM4)	453

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Frontmatter
[More information](#)

Contents	xiii
11.1.2 Surface-potential-based models (HiSIM, MM11, and PSP)	454
11.1.3 Charge-based models (EKV, ACM, and BSIM5)	458
11.2 Parameter extraction for first-order design	460
11.2.1 Specific current and threshold voltage	461
11.2.2 The slope factor	463
11.2.3 Mobility	465
11.3 Comparison between experiment and the ACM model in a 0.35-μm technology	467
11.4 Comparison between simulation and the ACM model in a 0.13-μm technology	470
11.5 The Early voltage	473
Problems	479
References	480
<i>Index</i>	483

Preface

Analog integrated circuits in bipolar technology, beginning with operational amplifiers and advancing to data conversion and communication circuits, were developed in the 1960s and matured during the 1970s. During this period, the metal–oxide–semiconductor (MOS) technology evolved for digital circuits because of its better efficiency in terms of silicon-area use and power consumption compared with bipolar digital technologies. To reduce the system cost and power consumption, chips including digital and analog circuits appeared in MOS technology in the late 1970s. The first analog circuits in MOS technology were for audio-frequency applications. With the scaling of the MOS technology, driven by the need for large-scale integration levels, enhanced performance and reduced cost, even radio-frequency (RF) applications in MOS technology have become possible. Compared with digital design, analog design requires much more careful device modeling, and for this reason analog designers were at the origin of many MOS modeling enhancements.

The strong similarities between the basic operating principles of many bipolar and MOS analog building blocks and circuits have led some textbook authors to combine their presentation. On the other hand, there are profound differences between bipolar and MOS circuits in terms of the electrical performance and design approaches, and for this reason other texts focus only on MOS analog circuits. In this textbook we take this area of specialization a step further, focusing on analog MOS circuits at transistor level, using an accurate but simple MOS transistor model for design in order to reduce the distance between hand design and simulation results. In place of the common approach of furnishing separate analytical formulas for the strong- and weak-inversion operation regions of a building block, we provide simple formulas that are valid in all operation regions, including moderate inversion. This unified design approach is particularly suitable for analog design in advanced complementary-metal–oxide–semiconductor (CMOS) technologies. In effect, for deep-submicron MOS technologies good design tradeoffs are often obtained with transistors operating in weak and moderate inversion. It should be observed that the conventional approach based on the asymptotic models of strong and weak inversion does not allow meaningful exploration of the design space.

The book starts with a short comparison between bipolar and MOS analog circuits. The main differences between bipolar and MOS transistors are emphasized, since superficial similarities between them often lead to erroneous results. The drawbacks of some classical MOS field-effect-transistor (FET) models, particularly those related to the choice of the source terminal as the reference, are explained. Chapter 2 presents an accurate model for the MOS transistor. Large- and small-signal models for low and high frequency, which are valid in all the operating regions, are presented. The important concept of inversion level is developed and explicit expressions for all large- and

small-signal parameters of transistors in terms of the inversion levels are provided. The main small-geometry effects are summarized. An overview of CMOS technology for designers and the basic properties of passive devices in CMOS technology are the subjects of Chapter 3. The models for integrated resistors and capacitors are developed with the necessary depth for analog design. Some good practices for designing MOS transistor layouts are summarized. Chapter 4 gives a unified modeling for mismatch and noise. With the shrinking of the MOSFET dimensions and reduction in the supply voltage of advanced technologies, the consideration of matching and noise has become even more important for analog design. Thus, we have included a detailed presentation of mismatch and noise in Chapter 4 so that they can be considered in the subsequent study of the basic circuits and building blocks.

Chapter 5 starts with the simple current mirror, one of the basic building blocks of analog circuits. The main cascode configurations and some advanced mirror topologies are then presented. We make a complete large- and small-signal analysis and include errors due to finite output resistance, mismatch, and noise. Chapter 6 deals with current sources and voltage references. Self-biased current sources and voltage references are described, emphasizing bandgap references. The whole chapter is dedicated to the basic bias building blocks, because bias and dc behavior are of the utmost importance in relation to analog circuits. In Chapter 7 the basic gain stages are described. Common-source, common-gate, source-follower, cascode, and differential amplifiers are thoroughly analyzed. The use of an all-region one-equation MOSFET model allows the complete exploration of the design space, and the choice of the best operating region (weak, moderate, or strong inversion) for each transistor involved. The important topic of CMOS design scaling and reuse is summarized at the end of the chapter. Chapter 8 deals with the design of operational amplifiers. The main topologies used in CMOS technology are presented, including single- and two-stage operational amplifiers. Fully differential amplifiers, including the folded-cascode type, and common-mode feedback circuits are described.

The following two chapters of the book introduce the basic circuit techniques for frequency-selective filters and some building blocks for data converters. In Chapter 9 the MOSFET-C filter technique derived from active *RC* filters is presented, followed by the basics of operational transconductance amplifier-capacitor (OTA-C) filters, including on-chip tuning circuits. Digitally-programmable filters using MOSFET-only current dividers (MOCDs) are also discussed.

In Chapter 10, following the analysis of analog MOS switches and sample-and-hold circuits, sampled-data techniques are introduced. Switched-capacitor building blocks for integrated filters and converters are described. The important topic of switched-capacitor filters fully compatible with digital MOS technology is covered. Finally, some complementary modeling topics considered important for circuit design are summarized in the appendices.

Chapter 11 provides an overview of compact MOSFET models, which play a significant role in the analysis and design of integrated circuits. This chapter also describes some procedures employed to extract fundamental design parameters associated with the MOSFET model used in this textbook.

This book is intended for an in-depth first course in analog CMOS design, for senior-undergraduate and first-year graduate students, as well as for self-study in the case of practicing engineers. The required background for the students is one or two introductory courses in electronics and in semiconductor devices.

Since analog-circuit design requires knowledge in the areas of device modeling, integrated-circuit technology, and layout, in addition to signals and circuits, the study of Chapters 1–4 is essential for any use of the book. A course focused on transistor-level design could be restricted to Chapters 1–8. A 15-week semester is sufficient to cover the whole book.

We are very grateful to our former PhD students Professors Ana Isabela Araújo Cunha, Oscar da Costa Gouveia Filho, Alfredo Arnaud, and Hamilton Klimach, who made invaluable contributions to the research on MOSFET modeling in our group and to the CNPq and CAPES, Brazilian agencies for scientific development, for their support of the research in our laboratory.

As in the past few years, we continue to have the collaboration of Dr. Siobhan Wiese for the revision of our texts. We are lucky to have a native English speaker with a scientific background to count on, as this is not always a rewarding task. We are also very grateful to João Romão for the skillful preparation of the figures. Last but not least, the hard work of Gustavo Leão Moreira for the simulations in Chapter 11 is gratefully acknowledged.