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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CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore,
São Paulo, Delhi, Dubai, Tokyo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521110365

First published 2010

Printed in the United Kingdom at the University Press, Cambridge

A catalogue record for this publication is available from the British Library

ISBN 978 0 521 11036 5 Hardback

Additional resources for this publication at www.cambridge.org/9780521110365

To our wives Rita and Marlene

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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.