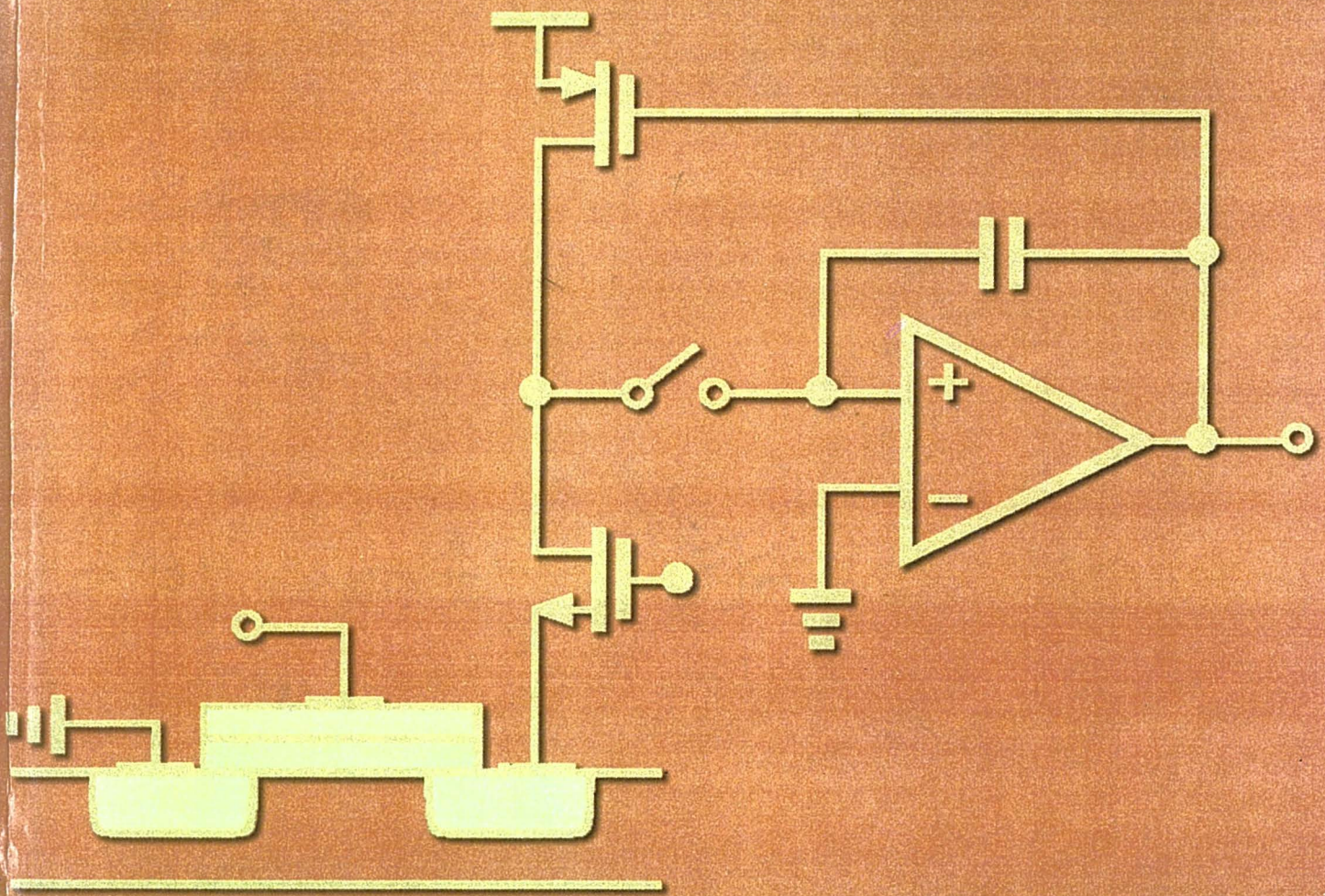




3 0611 00098 2817

Design of Analog CMOS Integrated Circuits



Behzad Razavi

Design of Analog CMOS Integrated Circuits

Behzad Razavi

Professor of Electrical Engineering
University of California, Los Angeles

ILLINOIS INSTITUTE OF TECHNOLOGY
PAUL V. GALVIN LIBRARY
35 WEST 33RD STREET
CHICAGO, IL 60616



Boston Burr Ridge, IL Dubuque, IA Madison, WI
New York San Francisco St. Louis
Bangkok Bogotá Caracas Lisbon London Madrid Mexico City
Milan New Delhi Seoul Singapore Sydney Taipei Toronto

McGraw-Hill Higher Education

A Division of The McGraw-Hill Companies

DESIGN OF ANALOG CMOS INTEGRATED CIRCUITS

Published by McGraw-Hill, an imprint of The McGraw-Hill Companies, Inc. 1221 Avenue of the Americas, New York, NY, 10020. Copyright © 2001, by The McGraw-Hill Companies, Inc. All rights reserved. No part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written consent of The McGraw-Hill Companies, Inc., including, but not limited to, in any network or other electronic storage or transmission, or broadcast for distance learning.

Some ancillaries, including electronic and print components, may not be available to customers outside the United States.

This book is printed on acid-free paper.

7 8 9 0 FGR/FGR 0 9 8 7

ISBN-13: 978-0-07-238032-3

ISBN-10: 0-07-238032-2

Vice president/Editor-in-chief: *Kevin T. Kane*

Publisher: *Thomas Casson*

Sponsoring editor: *Catherine Fields*

Developmental editor: *Michelle L. Flomenhoft*

Senior marketing manager: *John T. Wannemacher*

Project manager: *Jim Labeots*

Production supervisor: *Gina Hangos*

Senior designer: *Kiera Cunningham*

New media: *Phillip Meek*

Compositor: *Interactive Composition Corporation*

Typeface: *10/12 Times Roman*

Printer: *Quebecor World Fairfield*

Library of Congress Cataloging-in-Publication Data

Razavi, Behzad.

Design of analog CMOS integrated circuits / Behzad Razavi.

p. cm.

ISBN 0-07-238032-2 (alk. paper)

1. Linear integrated circuits—Design and construction. 2. Metal oxide semiconductors. Complementary. I. Title.

TK7874.654. R39 2001

621.39'732—dc21

00-044789

Contents

About the Author	vii
Preface	ix
Acknowledgments	xi
1 Introduction to Analog Design	1
1.1 Why Analog?	1
1.2 Why Integrated?	6
1.3 Why CMOS?	6
1.4 Why This Book?	7
1.5 General Concepts	7
1.5.1 Levels of Abstraction	7
1.5.2 Robust Analog Design	7
2 Basic MOS Device Physics	9
2.1 General Considerations	10
2.1.1 MOSFET as a Switch	10
2.1.2 MOSFET Structure	10
2.1.3 MOS Symbols	12
2.2 MOS I/V Characteristics	13
2.2.1 Threshold Voltage	13
2.2.2 Derivation of I/V Characteristics	15
2.3 Second-Order Effects	23
2.4 MOS Device Models	28
2.4.1 MOS Device Layout	28
2.4.2 MOS Device Capacitances	29
2.4.3 MOS Small-Signal Model	33
2.4.4 MOS SPICE models	36
2.4.5 NMOS versus PMOS Devices	37
2.4.6 Long-Channel versus Short-Channel Devices	38

3	Single-Stage Amplifiers	47
3.1	Basic Concepts	47
3.2	Common-Source Stage	48
3.2.1	Common-Source Stage with Resistive Load	48
3.2.2	CS Stage with Diode-Connected Load	53
3.2.3	CS Stage with Current-Source Load	58
3.2.4	CS Stage with Triode Load	59
3.2.5	CS Stage with Source Degeneration	60
3.3	Source Follower	67
3.4	Common-Gate Stage	76
3.5	Cascode Stage	83
3.5.1	Folded Cascode	90
3.6	Choice of Device Models	92
4	Differential Amplifiers	100
4.1	Single-Ended and Differential Operation	100
4.2	Basic Differential Pair	103
4.2.1	Qualitative Analysis	104
4.2.2	Quantitative Analysis	107
4.3	Common-Mode Response	118
4.4	Differential Pair with MOS Loads	124
4.5	Gilbert Cell	126
5	Passive and Active Current Mirrors	135
5.1	Basic Current Mirrors	135
5.2	Cascode Current Mirrors	139
5.3	Active Current Mirrors	145
5.3.1	Large-Signal Analysis	149
5.3.2	Small-Signal Analysis	151
5.3.3	Common-Mode Properties	154
6	Frequency Response of Amplifiers	166
6.1	General Considerations	166
6.1.1	Miller Effect	166
6.1.2	Association of Poles with Nodes	169
6.2	Common-Source Stage	172
6.3	Source Followers	178
6.4	Common-Gate Stage	183
6.5	Cascode Stage	185
6.6	Differential Pair	187
	Appendix A: Dual of Miller's Theorem	193

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts



Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research



With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips



Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.