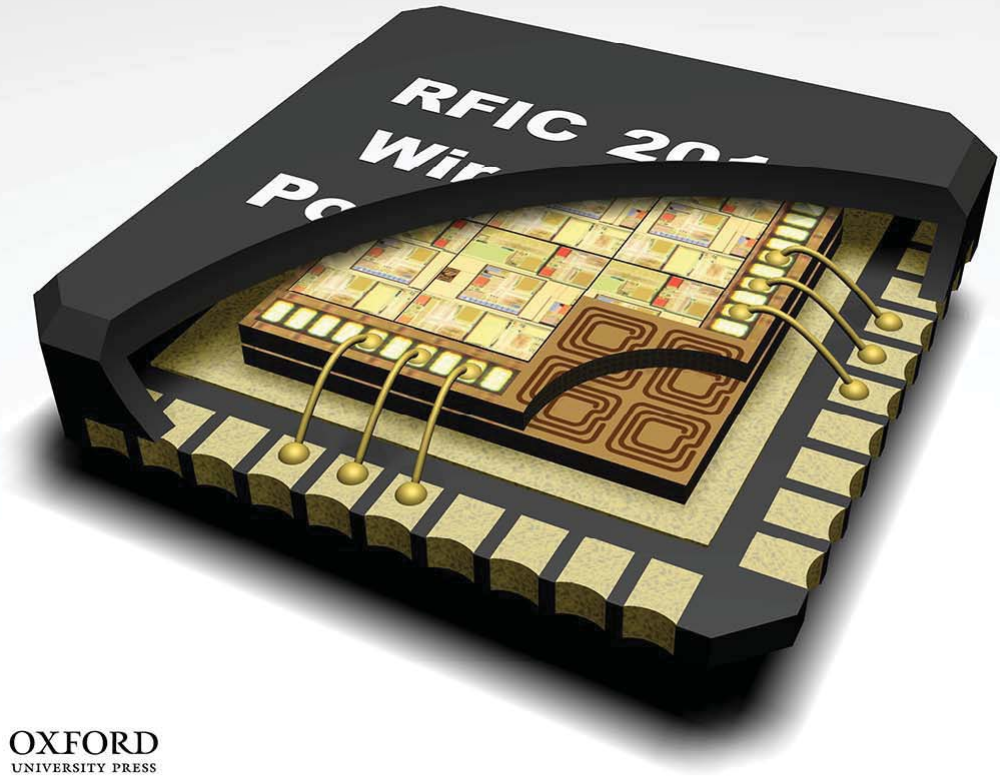
SEDRA/SMITH

Microelectronic Circuits

SEVENTH EDITION



OXFORD
UNIVERSITY PRESS

Microelectronic Circuits

THE OXFORD SERIES IN ELECTRICAL AND COMPUTER ENGINEERING

Adel S. Sedra, Series Editor

Allen and Holberg, *CMOS Analog Circuit Design, 3rd edition*
Bobrow, *Elementary Linear Circuit Analysis, 2nd edition*
Bobrow, *Fundamentals of Electrical Engineering, 2nd edition*
Campbell, *Fabrication Engineering at the Micro- and Nanoscale, 4th edition*
Chen, *Digital Signal Processing*
Chen, *Linear System Theory and Design, 4th edition*
Chen, *Signals and Systems, 3rd edition*
Comer, *Digital Logic and State Machine Design, 3rd edition*
Comer, *Microprocessor-Based System Design*
Cooper and McGillem, *Probabilistic Methods of Signal and System Analysis, 3rd edition*
Dimitrijev, *Principles of Semiconductor Device, 2nd edition*
Dimitrijev, *Understanding Semiconductor Devices*
Fortney, *Principles of Electronics: Analog & Digital*
Franco, *Electric Circuits Fundamentals*
Ghausi, *Electronic Devices and Circuits: Discrete and Integrated*
Guru and Hiziroğlu, *Electric Machinery and Transformers, 3rd edition*
Houts, *Signal Analysis in Linear Systems*
Jones, *Introduction to Optical Fiber Communication Systems*
Krein, *Elements of Power Electronics*
Kuo, *Digital Control Systems, 2nd edition*
Lathi, *Linear Systems and Signals, 2nd edition*
Lathi and Ding, *Modern Digital and Analog Communication Systems, 4th edition*
Lathi, *Signal Processing and Linear Systems*
Martin, *Digital Integrated Circuit Design*
Miner, *Lines and Electromagnetic Fields for Engineers*
Parhami, *Computer Architecture*
Parhami, *Computer Arithmetic, 2nd edition*
Roberts and Sedra, *SPICE, 2nd edition*
Roberts, Taenzler, and Burns, *An Introduction to Mixed-Signal IC Test and Measurement, 2nd edition*
Roulston, *An Introduction to the Physics of Semiconductor Devices*
Sadiku, *Elements of Electromagnetics, 6th edition*
Santina, Stubberud, and Hostetter, *Digital Control System Design, 2nd edition*
Sarma, *Introduction to Electrical Engineering*
Schaumann, Xiao, and Van Valkenburg, *Design of Analog Filters, 3rd edition*
Schwarz and Oldham, *Electrical Engineering: An Introduction, 2nd edition*
Sedra and Smith, *Microelectronic Circuits, 7th edition*
Stefani, Shahian, Savant, and Hostetter, *Design of Feedback Control Systems, 4th edition*
Tsividis/McAndrew, *Operation and Modeling of the MOS Transistor, 3rd edition*
Van Valkenburg, *Analog Filter Design*
Warner and Grung, *Semiconductor Device Electronics*
Wolovich, *Automatic Control Systems*
Yariv and Yeh, *Photonics: Optical Electronics in Modern Communications, 6th edition*
Żak, *Systems and Control*

SEVENTH EDITION

Microelectronic Circuits

Adel S. Sedra
University of Waterloo

Kenneth C. Smith
University of Toronto

New York Oxford
OXFORD UNIVERSITY PRESS

Oxford University Press is a department of the University of Oxford. It furthers the University's objective of excellence in research, scholarship, and education by publishing worldwide.

Oxford New York
Auckland Cape Town Dar es Salaam Hong Kong Karachi
Kuala Lumpur Madrid Melbourne Mexico City Nairobi
New Delhi Shanghai Taipei Toronto

With offices in
Argentina Austria Brazil Chile Czech Republic France Greece
Guatemala Hungary Italy Japan Poland Portugal Singapore
South Korea Switzerland Thailand Turkey Ukraine Vietnam

Copyright © 2015, 2010, 2004, 1998 by Oxford University Press;
1991, 1987 Holt, Rinehart, and Winston, Inc.; 1982 CBS College Publishing

For titles covered by Section 112 of the US Higher Education Opportunity Act, please visit www.oup.com/us/he for the latest information about pricing and alternate formats.

Published in the United States of America by
Oxford University Press
198 Madison Avenue, New York, NY 10016
http://www.oup.com

Oxford is a registered trade mark of Oxford University Press.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior permission of Oxford University Press.

Library of Congress Cataloging-in-Publication Data

Sedra, Adel S., author.
Microelectronic circuits / Adel S. Sedra, University of Waterloo, Kenneth C. Smith, University of Toronto. — Seventh edition.
pages cm. — (The Oxford series in electrical and computer engineering)
Includes bibliographical references and index.
ISBN 978–0–19–933913–6
1. Electronic circuits. 2. Integrated circuits. I. Smith, Kenneth C. (Kenneth Carless), author. II. Title.
TK7867.S39 2014
621.3815—dc23 2014033965

Multisim and National Instruments are trademarks of National Instruments. The Sedra/Smith, *Microelectronic Circuits*, Seventh Edition book is a product of Oxford University Press, not National Instruments Corporation or any of its affiliated companies, and Oxford University Press is solely responsible for the Sedra/Smith book and its content. Neither Oxford University Press, the Sedra/Smith book, nor any of the books and other goods and services offered by Oxford University Press are official publications of National Instruments Corporation or any of its affiliated companies, and they are not affiliated with, endorsed by, or sponsored by National Instruments Corporation or any of its affiliated companies.

OrCad and PSpice are trademarks of Cadence Design Systems, Inc. The Sedra/Smith, *Microelectronic Circuits*, Seventh Edition book is a product of Oxford University Press, not Cadence Design Systems, Inc., or any of its affiliated companies, and Oxford University Press is solely responsible for the Sedra/Smith book and its content. Neither Oxford University Press, the Sedra/Smith book, nor any of the books and other goods and services offered by Oxford University Press are official publications of Cadence Design Systems, Inc. or any of its affiliated companies, and they are not affiliated with, endorsed by, or sponsored by Cadence Design Systems, Inc. or any of its affiliated companies.

Cover Photo: This 3D IC system demonstrates the concept of wireless power delivery and communication through multiple layers of CMOS chips. The communication circuits were demonstrated in an IBM 45 nm SOI CMOS process. This technology is designed to serve a multi-Gb/s interconnect between cores spread across several IC layers for high-performance processors.
(Photo Credit: The picture is courtesy of Professor David Wentzloff, Director of the Wireless Integrated Circuits Group at the University of Michigan, and was edited by Muhammad Faisal, Founder of Movellus Circuits Incorporated.)

Printing number: 9 8 7 6 5 4 3 2 1

Printed in the United States of America
on acid-free paper

BRIEF TABLE OF CONTENTS

Tables xvi
"Expand-Your-Perspective" Notes xvii
Preface xix

PART I **DEVICES AND BASIC CIRCUITS** 2

1 Signals and Amplifiers 4
2 Operational Amplifiers 58
3 Semiconductors 134
4 Diodes 174
5 MOS Field-Effect Transistors (MOSFETs) 246
6 Bipolar Junction Transistors (BJTs) 304
7 Transistor Amplifiers 366

PART II **INTEGRATED-CIRCUIT AMPLIFIERS** 506

8 Building Blocks of Integrated-Circuit Amplifiers 508
9 Differential and Multistage Amplifiers 594
10 Frequency Response 696
11 Feedback 806
12 Output Stages and Power Amplifiers 920
13 Operational Amplifier Circuits 994

PART III **DIGITAL INTEGRATED CIRCUITS** 1086

14 CMOS Digital Logic Circuits 1088
15 Advanced Topics in Digital Integrated-Circuit Design 1166
16 Memory Circuits 1236

PART IV **FILTERS AND OSCILLATORS** 1288

17 Filters and Tuned Amplifiers 1290
18 Signal Generators and Waveform-Shaping Circuits 1378

Appendices A–L

Index IN-1

CONTENTS

Tables xvi
"Expand-Your-Perspective" Notes xvii
Preface xix

PART I DEVICES AND BASIC CIRCUITS 2

1 Signals and Amplifiers 4
Introduction 5
1.1 Signals 6
1.2 Frequency Spectrum of Signals 9
1.3 Analog and Digital Signals 12
1.4 Amplifiers 15
1.4.1 Signal Amplification 15
1.4.2 Amplifier Circuit Symbol 16
1.4.3 Voltage Gain 17
1.4.4 Power Gain and Current Gain 17
1.4.5 Expressing Gain in Decibels 18
1.4.6 The Amplifier Power Supplies 18
1.4.7 Amplifier Saturation 21
1.4.8 Symbol Convention 22
1.5 Circuit Models for Amplifiers 23
1.5.1 Voltage Amplifiers 23
1.5.2 Cascaded Amplifiers 25
1.5.3 Other Amplifier Types 28
1.5.4 Relationships between the Four Amplifier Models 28
1.5.5 Determining R_i and R_o 29
1.5.6 Unilateral Models 29
1.6 Frequency Response of Amplifiers 33
1.6.1 Measuring the Amplifier Frequency Response 33
1.6.2 Amplifier Bandwidth 34
1.6.3 Evaluating the Frequency Response of Amplifiers 34
1.6.4 Single-Time-Constant Networks 35
1.6.5 Classification of Amplifiers Based on Frequency Response 41
Summary 44
Problems 45

2 Operational Amplifiers 58
Introduction 59
2.1 The Ideal Op Amp 60
2.1.1 The Op-Amp Terminals 60
2.1.2 Function and Characteristics of the Ideal Op Amp 61
2.1.3 Differential and Common-Mode Signals 63
2.2 The Inverting Configuration 64
2.2.1 The Closed-Loop Gain 65
2.2.2 Effect of the Finite Open-Loop Gain 67
2.2.3 Input and Output Resistances 68
2.2.4 An Important Application—The Weighted Summer 71
2.3 The Noninverting Configuration 73
2.3.1 The Closed-Loop Gain 73
2.3.2 Effect of Finite Open-Loop Gain 75
2.3.3 Input and Output Resistance 75
2.3.4 The Voltage Follower 75
2.4 Difference Amplifiers 77
2.4.1 A Single-Op-Amp Difference Amplifier 78
2.4.2 A Superior Circuit—The Instrumentation Amplifier 82
2.5 Integrators and Differentiators 87
2.5.1 The Inverting Configuration with General Impedances 87
2.5.2 The Inverting Integrator 89
2.5.3 The Op-Amp Differentiator 94
2.6 DC Imperfections 96
2.6.1 Offset Voltage 96
2.6.2 Input Bias and Offset Currents 100
2.6.3 Effect of V_{OS} and I_{OS} on the Operation of the Inverting Integrator 103
2.7 Effect of Finite Open-Loop Gain and Bandwidth on Circuit Performance 105
2.7.1 Frequency Dependence of the Open-Loop Gain 105
2.7.2 Frequency Response of Closed-Loop Amplifiers 107

2.8 Large-Signal Operation of Op Amps **110**
2.8.1 Output Voltage Saturation **110**
2.8.2 Output Current Limits **110**
2.8.3 Slew Rate **112**
2.8.4 Full-Power Bandwidth **114**
Summary **115**
Problems **116**

3 Semiconductors 134
Introduction **135**
3.1 Intrinsic Semiconductors **136**
3.2 Doped Semiconductors **139**
3.3 Current Flow in Semiconductors **142**
3.3.1 Drift Current **142**
3.3.2 Diffusion Current **145**
3.3.3 Relationship between D and μ **148**
3.4 The *pn* Junction **148**
3.4.1 Physical Structure **149**
3.4.2 Operation with Open-Circuit Terminals **149**
3.5 The *pn* Junction with an Applied Voltage **155**
3.5.1 Qualitative Description of Junction Operation **155**
3.5.2 The Current–Voltage Relationship of the Junction **158**
3.5.3 Reverse Breakdown **162**
3.6 Capacitive Effects in the *pn* Junction **164**
3.6.1 Depletion or Junction Capacitance **164**
3.6.2 Diffusion Capacitance **166**
Summary **168**
Problems **171**

4 Diodes 174
Introduction **175**
4.1 The Ideal Diode **176**
4.1.1 Current–Voltage Characteristic **176**
4.1.2 A Simple Application: The Rectifier **177**
4.1.3 Another Application: Diode Logic Gates **180**
4.2 Terminal Characteristics of Junction Diodes **184**
4.2.1 The Forward-Bias Region **184**
4.2.2 The Reverse-Bias Region **189**
4.2.3 The Breakdown Region **190**
4.3 Modeling the Diode Forward Characteristic **190**
4.3.1 The Exponential Model **190**
4.3.2 Graphical Analysis Using the Exponential Model **191**
4.3.3 Iterative Analysis Using the Exponential Model **191**
4.3.4 The Need for Rapid Analysis **192**
4.3.5 The Constant-Voltage-Drop Model **193**
4.3.6 The Ideal-Diode Model **194**
4.3.7 The Small-Signal Model **195**
4.3.8 Use of the Diode Forward Drop in Voltage Regulation **200**
4.4 Operation in the Reverse Breakdown Region—Zener Diodes **202**
4.4.1 Specifying and Modeling the Zener Diode **203**
4.4.2 Use of the Zener as a Shunt Regulator **204**
4.4.3 Temperature Effects **206**
4.4.4 A Final Remark **207**
4.5 Rectifier Circuits **207**
4.5.1 The Half-Wave Rectifier **208**
4.5.2 The Full-Wave Rectifier **210**
4.5.3 The Bridge Rectifier **212**
4.5.4 The Rectifier with a Filter Capacitor—The Peak Rectifier **213**
4.5.5 Precision Half-Wave Rectifier—The Superdiode **219**
4.6 Limiting and Clamping Circuits **221**
4.6.1 Limiter Circuits **221**
4.6.2 The Clamped Capacitor or DC Restorer **224**
4.6.3 The Voltage Doubler **226**
4.7 Special Diode Types **227**
4.7.1 The Schottky-Barrier Diode (SBD) **227**
4.7.2 Varactors **228**
4.7.3 Photodiodes **228**
4.7.4 Light-Emitting Diodes (LEDs) **228**
Summary **229**
Problems **230**

5 MOS Field-Effect Transistors (MOSFETs) 246
Introduction **247**
5.1 Device Structure and Physical Operation **248**
5.1.1 Device Structure **248**
5.1.2 Operation with Zero Gate Voltage **250**

5.1.3 Creating a Channel for Current Flow **250**
5.1.4 Applying a Small v_{DS} **252**
5.1.5 Operation as v_{DS} Is Increased **256**
5.1.6 Operation for $v_{DS} \geq V_{OV}$: Channel Pinch-Off and Current Saturation **258**
5.1.7 The *p*-Channel MOSFET **261**
5.1.8 Complementary MOS or CMOS **263**
5.1.9 Operating the MOS Transistor in the Subthreshold Region **264**
5.2 Current–Voltage Characteristics **264**
5.2.1 Circuit Symbol **264**
5.2.2 The i_D–v_{DS} Characteristics **265**
5.2.3 The i_D–v_{GS} Characteristic **267**
5.2.4 Finite Output Resistance in Saturation **271**
5.2.5 Characteristics of the *p*-Channel MOSFET **274**
5.3 MOSFET Circuits at DC **276**
5.4 The Body Effect and Other Topics **288**
5.4.1 The Role of the Substrate—The Body Effect **288**
5.4.2 Temperature Effects **289**
5.4.3 Breakdown and Input Protection **289**
5.4.4 Velocity Saturation **290**
5.4.5 The Depletion-Type MOSFET **290**
Summary **291**
Problems **292**

6 Bipolar Junction Transistors (BJTs) 304

Introduction **305**
6.1 Device Structure and Physical Operation **306**
6.1.1 Simplified Structure and Modes of Operation **306**
6.1.2 Operation of the *npn* Transistor in the Active Mode **307**
6.1.3 Structure of Actual Transistors **315**
6.1.4 Operation in the Saturation Mode **316**
6.1.5 The *pnp* Transistor **318**
6.2 Current–Voltage Characteristics **320**
6.2.1 Circuit Symbols and Conventions **320**
6.2.2 Graphical Representation of Transistor Characteristics **325**
6.2.3 Dependence of i_C on the Collector Voltage—The Early Effect **326**
6.2.4 An Alternative Form of the Common-Emitter Characteristics **329**
6.3 BJT Circuits at DC **333**
6.4 Transistor Breakdown and Temperature Effects **351**
6.4.1 Transistor Breakdown **351**
6.4.2 Dependence of β on I_C and Temperature **353**
Summary **354**
Problems **355**

7 Transistor Amplifiers 366

Introduction **367**
7.1 Basic Principles **368**
7.1.1 The Basis for Amplifier Operation **368**
7.1.2 Obtaining a Voltage Amplifier **369**
7.1.3 The Voltage-Transfer Characteristic (VTC) **370**
7.1.4 Obtaining Linear Amplification by Biasing the Transistor **371**
7.1.5 The Small-Signal Voltage Gain **374**
7.1.6 Determining the VTC by Graphical Analysis **380**
7.1.7 Deciding on a Location for the Bias Point Q **381**
7.2 Small-Signal Operation and Models **383**
7.2.1 The MOSFET Case **383**
7.2.2 The BJT Case **399**
7.2.3 Summary Tables **420**
7.3 Basic Configurations **423**
7.3.1 The Three Basic Configurations **423**
7.3.2 Characterizing Amplifiers **424**
7.3.3 The Common-Source (CS) and Common-Emitter (CE) Amplifiers **426**
7.3.4 The Common-Source (Common-Emitter) Amplifier with a Source (Emitter) Resistance **431**
7.3.5 The Common-Gate (CG) and the Common-Base (CB) Amplifiers **439**
7.3.6 The Source and Emitter Followers **442**
7.3.7 Summary Tables and Comparisons **452**

7.3.8 When and How to Include the Transistor Output Resistance r_o **453**
7.4 Biasing **454**
7.4.1 The MOSFET Case **455**
7.4.2 The BJT Case **461**
7.5 Discrete-Circuit Amplifiers **467**
7.5.1 A Common-Source (CS) Amplifier **467**
7.5.2 A Common-Emitter (CE) Amplifier **470**
7.5.3 A Common-Emitter Amplifier with an Emitter Resistance R_e **471**
7.5.4 A Common-Base (CB) Amplifier **473**
7.5.5 An Emitter Follower **475**
7.5.6 The Amplifier Frequency Response **477**
Summary **479**
Problems **480**

PART II **INTEGRATED-CIRCUIT AMPLIFIERS 506**

8 Building Blocks of Integrated-Circuit Amplifiers 508

Introduction **509**
8.1 IC Design Philosophy **510**
8.2 IC Biasing—Current Sources, Current Mirrors, and Current-Steering Circuits **511**
8.2.1 The Basic MOSFET Current Source **512**
8.2.2 MOS Current-Steering Circuits **515**
8.2.3 BJT Circuits **518**
8.2.4 Small-Signal Operation of Current Mirrors **523**
8.3 The Basic Gain Cell **525**
8.3.1 The CS and CE Amplifiers with Current-Source Loads **525**
8.3.2 The Intrinsic Gain **527**
8.3.3 Effect of the Output Resistance of the Current-Source Load **530**
8.3.4 Increasing the Gain of the Basic Cell **536**
8.4 The Common-Gate and Common-Base Amplifiers **537**
8.4.1 The CG Circuit **537**
8.4.2 Output Resistance of a CS Amplifier with a Source Resistance **541**
8.4.3 The Body Effect **542**
8.4.4 The CB Circuit **543**
8.4.5 Output Resistance of an Emitter-Degenerated CE Amplifier **546**
8.5 The Cascode Amplifier **546**
8.5.1 Cascoding **546**
8.5.2 The MOS Cascode Amplifier **547**
8.5.3 Distribution of Voltage Gain in a Cascode Amplifier **552**
8.5.4 Double Cascoding **555**
8.5.5 The Folded Cascode **555**
8.5.6 The BJT Cascode **557**
8.6 Current-Mirror Circuits with Improved Performance **559**
8.6.1 Cascode MOS Mirrors **559**
8.6.2 The Wilson Current Mirror **560**
8.6.3 The Wilson MOS Mirror **563**
8.6.4 The Widlar Current Souce **565**
8.7 Some Useful Transistor Pairings **567**
8.7.1 The CC–CE, CD–CS, and CD–CE Configurations **567**
8.7.2 The Darlington Configuration **571**
8.7.3 The CC–CB and CD–CG Configurations **572**
Summary **575**
Problems **576**

9 Differential and Multistage Amplifiers 594

Introduction **595**
9.1 The MOS Differential Pair **596**
9.1.1 Operation with a Common-Mode Input Voltage **597**
9.1.2 Operation with a Differential Input Voltage **601**
9.1.3 Large-Signal Operation **602**
9.1.4 Small-Signal Operation **607**
9.1.5 The Differential Amplifier with Current-Source Loads **611**
9.1.6 Cascode Differential Amplifier **612**
9.2 The BJT Differential Pair **614**
9.2.1 Basic Operation **614**
9.2.2 Input Common-Mode Range **616**
9.2.3 Large-Signal Operation **617**
9.2.4 Small-Signal Operation **620**
9.3 Common-Mode Rejection **627**
9.3.1 The MOS Case **628**
9.3.2 The BJT Case **634**
9.4 DC Offset **637**

9.4.1 Input Offset Voltage of the MOS Differential Amplifier **637**
9.4.2 Input Offset Voltage of the Bipolar Differential Amplifier **640**
9.4.3 Input Bias and Offset Currents of the Bipolar Differential Amplifier **643**
9.4.4 A Concluding Remark **644**
9.5 The Differential Amplifier with a Current-Mirror Load **644**
9.5.1 Differential to Single-Ended Conversion **644**
9.5.2 The Current-Mirror-Loaded MOS Differential Pair **645**
9.5.3 Differential Gain of the Current-Mirror-Loaded MOS Pair **647**
9.5.4 The Bipolar Differential Pair with a Current-Mirror Load **651**
9.5.5 Common-Mode Gain and CMRR **655**
9.6 Multistage Amplifiers **659**
9.6.1 A Two-Stage CMOS Op Amp **659**
9.6.2 A Bipolar Op Amp **664**
Summary **672**
Problems **674**

10 Frequency Response 696

Introduction **697**
10.1 Low-Frequency Response of Discrete-Circuit Common-Source and Common-Emitter Amplifiers **699**
10.1.1 The CS Amplifier **699**
10.1.2 The Method of Short-Circuit Time-Constants **707**
10.1.3 The CE Amplifier **707**
10.2 Internal Capacitive Effects and the High-Frequency Model of the MOSFET and the BJT **711**
10.2.1 The MOSFET **711**
10.2.2 The BJT **717**
10.3 High-Frequency Response of the CS and CE Amplifiers **722**
10.3.1 The Common-Source Amplifier **722**
10.3.2 The Common-Emitter Amplifier **728**
10.3.3 Miller's Theorem **732**
10.3.4 Frequency Response of the CS Amplifier When R_{sig} Is Low **735**
10.4 Useful Tools for the Analysis of the High-Frequency Response of Amplifiers **739**
10.4.1 The High-Frequency Gain Function **739**
10.4.2 Determining the 3-dB Frequency f_H **740**
10.4.3 The Method of Open-Circuit Time Constants **743**
10.4.4 Application of the Method of Open-Circuit Time Constants to the CS Amplifier **744**
10.4.5 Application of the Method of Open-Circuit Time Constants to the CE Amplifier **748**
10.5 High-Frequency Response of the Common-Gate and Cascode Amplifiers **748**
10.5.1 High-Frequency Response of the CG Amplifier **748**
10.5.2 High-Frequency Response of the MOS Cascode Amplifier **754**
10.5.3 High-Frequency Response of the Bipolar Cascode Amplifier **759**
10.6 High-Frequency Response of the Source and Emitter Followers **760**
10.6.1 The Source-Follower Case **761**
10.6.2 The Emitter-Follower Case **767**
10.7 High-Frequency Response of Differential Amplifiers **768**
10.7.1 Analysis of the Resistively Loaded MOS Amplifier **768**
10.7.2 Analysis of the Current-Mirror-Loaded MOS Amplifier **772**
10.8 Other Wideband Amplifier Configurations **778**
10.8.1 Obtaining Wideband Amplification by Source and Emitter Degeneration **778**
10.8.2 The CD–CS, CC–CE, and CD–CE Configurations **781**
10.8.3 The CC–CB and CD–CG Configurations **786**
Summary **788**
Problems **789**

11 Feedback 806

Introduction **807**
11.1 The General Feedback Structure **808**
11.1.1 Signal-Flow Diagram **808**
11.1.2 The Closed-Loop Gain **809**

11.1.3 The Loop Gain **810**
11.1.4 Summary **814**
11.2 Some Properties of Negative Feedback **815**
11.2.1 Gain Desensitivity **815**
11.2.2 Bandwidth Extension **816**
11.2.3 Interference Reduction **817**
11.2.4 Reduction in Nonlinear Distortion **819**
11.3 The Feedback Voltage Amplifier **820**
11.3.1 The Series–Shunt Feedback Topology **820**
11.3.2 Examples of Series–Shunt Feedback Amplifiers **821**
11.3.3 Analysis of the Feedback Voltage Amplifier Utilizing the Loop Gain **823**
11.3.4 A Final Remark **828**
11.4 Systematic Analysis of Feedback Voltage Amplifiers **828**
11.4.1 The Ideal Case **829**
11.4.2 The Practical Case **831**
11.5 Other Feedback Amplifier Types **840**
11.5.1 Basic Principles **840**
11.5.2 The Feedback Transconductance Amplifier (Series–Series) **844**
11.5.3 The Feedback Transresistance Amplifier (Shunt–Shunt) **855**
11.5.4 The Feedback Current Amplifier (Shunt–Series) **865**
11.6 Summary of the Feedback Analysis Method **871**
11.7 The Stability Problem **871**
11.7.1 Transfer Function of the Feedback Amplifier **871**
11.7.2 The Nyquist Plot **873**
11.8 Effect of Feedback on the Amplifier Poles **875**
11.8.1 Stability and Pole Location **875**
11.8.2 Poles of the Feedback Amplifier **876**
11.8.3 Amplifier with a Single-Pole Response **877**
11.8.4 Amplifier with a Two-Pole Response **878**
11.8.5 Amplifiers with Three or More Poles **883**
11.9 Stability Study Using Bode Plots **885**
11.9.1 Gain and Phase Margins **885**
11.9.2 Effect of Phase Margin on Closed-Loop Response **886**
11.9.3 An Alternative Approach for Investigating Stability **887**
11.10 Frequency Compensation **889**
11.10.1 Theory **889**
11.10.2 Implementation **891**
11.10.3 Miller Compensation and Pole Splitting **892**
Summary **895**
Problems **896**

12 Output Stages and Power Amplifiers 920

Introduction **921**
12.1 Classification of Output Stages **922**
12.2 Class A Output Stage **923**
12.2.1 Transfer Characteristic **924**
12.2.2 Signal Waveforms **925**
12.2.3 Power Dissipation **926**
12.2.4 Power-Conversion Efficiency **928**
12.3 Class B Output Stage **929**
12.3.1 Circuit Operation **929**
12.3.2 Transfer Characteristic **929**
12.3.3 Power-Conversion Efficiency **930**
12.3.4 Power Dissipation **931**
12.3.5 Reducing Crossover Distortion **933**
12.3.6 Single-Supply Operation **934**
12.4 Class AB Output Stage **935**
12.4.1 Circuit Operation **935**
12.4.2 Output Resistance **937**
12.5 Biasing the Class AB Circuit **940**
12.5.1 Biasing Using Diodes **940**
12.5.2 Biasing Using the V_{BE} Multiplier **942**
12.6 Variations on the Class AB Configuration **945**
12.6.1 Use of Input Emitter Followers **945**
12.6.2 Use of Compound Devices **946**
12.6.3 Short-Circuit Protection **949**
12.6.4 Thermal Shutdown **950**
12.7 CMOS Class AB Output Stages **950**
12.7.1 The Classical Configuration **950**
12.7.2 An Alternative Circuit Utilizing Common-Source Transistors **953**
12.8 IC Power Amplifiers **961**
12.8.1 A Fixed-Gain IC Power Amplifier **962**

12.8.2 The Bridge Amplifier **966**
12.9 Class D Power Amplifiers **967**
12.10 Power Transistors **971**
12.10.1 Packages and Heat Sinks **971**
12.10.2 Power BJTs **972**
12.10.3 Power MOSFETs **974**
12.10.4 Thermal Considerations **976**
Summary **982**
Problems **983**

13 Operational-Amplifier Circuits 994

Introduction **995**
13.1 The Two-Stage CMOS Op Amp **996**
13.1.1 The Circuit **997**
13.1.2 Input Common-Mode Range and Output Swing **998**
13.1.3 DC Voltage Gain **999**
13.1.4 Common-Mode Rejection Ratio (CMRR) **1001**
13.1.5 Frequency Response **1002**
13.1.6 Slew Rate **1007**
13.1.7 Power-Supply Rejection Ratio (PSRR) **1008**
13.1.8 Design Trade-Offs **1009**
13.1.9 A Bias Circuit for the Two-Stage CMOS Op Amp **1010**
13.2 The Folded-Cascode CMOS Op Amp **1016**
13.2.1 The Circuit **1016**
13.2.2 Input Common-Mode Range and Output Swing **1018**
13.2.3 Voltage Gain **1020**
13.2.4 Frequency Response **1021**
13.2.5 Slew Rate **1022**
13.2.6 Increasing the Input Common-Mode Range: Rail-to-Rail Input Operation **1024**
13.2.7 Increasing the Output Voltage Range: The Wide-Swing Current Mirror **1026**
13.3 The 741 BJT Op Amp **1028**
13.3.1 The 741 Circuit **1028**
13.3.2 DC Analysis **1032**
13.3.3 Small-Signal Analysis **1038**
13.3.4 Frequency Response **1051**
13.3.5 Slew Rate **1053**
13.4 Modern Techniques for the Design of BJT Op Amps **1054**
13.4.1 Special Performance Requirements **1054**
13.4.2 Bias Design **1056**
13.4.3 Design of the Input Stage to Obtain Rail-to-Rail V_{ICM} **1058**
13.4.4 Common-Mode Feedback to Control the DC Voltage at the Output of the Input Stage **1064**
13.4.5 Output-Stage Design for Near Rail-to-Rail Output Swing **1069**
13.4.6 Concluding Remark **1073**
Summary **1073**
Problems **1074**

PART III **DIGITAL INTEGRATED CIRCUITS 1086**

14 CMOS Digital Logic Circuits 1088

Introduction **1089**
14.1 CMOS Logic-Gate Circuits **1090**
14.1.1 Switch-Level Transistor Model **1090**
14.1.2 The CMOS Inverter **1091**
14.1.3 General Structure of CMOS Logic **1091**
14.1.4 The Two-Input NOR Gate **1094**
14.1.5 The Two-Input NAND Gate **1095**
14.1.6 A Complex Gate **1096**
14.1.7 Obtaining the PUN from the PDN and Vice Versa **1096**
14.1.8 The Exclusive-OR Function **1097**
14.1.9 Summary of the Synthesis Method **1098**
14.2 Digital Logic Inverters **1100**
14.2.1 The Voltage-Transfer Characteristic (VTC) **1100**
14.2.2 Noise Margins **1101**
14.2.3 The Ideal VTC **1103**
14.2.4 Inverter Implementation **1103**
14.3 The CMOS Inverter **1114**
14.3.1 Circuit Operation **1114**
14.3.2 The Voltage-Transfer Characteristic (VTC) **1117**
14.3.3 The Situation When Q_N and Q_P Are Not Matched **1120**
14.4 Dynamic Operation of the CMOS Inverter **1125**

14.4.1 Propagation Delay **1125**
14.4.2 Determining the Propagation Delay of the CMOS Inverter **1129**
14.4.3 Determining the Equivalent Load Capacitance C **1136**
14.5 Transistor Sizing **1139**
14.5.1 Inverter Sizing **1139**
14.5.2 Transistor Sizing in CMOS Logic Gates **1141**
14.5.3 Effects of Fan-In and Fan-Out on Propagation Delay **1145**
14.5.4 Driving a Large Capacitance **1146**
14.6 Power Dissipation **1149**
14.6.1 Sources of Power Dissipation **1149**
14.6.2 Power–Delay and Energy–Delay Products **1152**
Summary **1154**
Problems **1156**

15 Advanced Topics in Digital Integrated-Circuit Design 1166

Introduction **1167**
15.1 Implications of Technology Scaling: Issues in Deep-Submicron Design **1168**
15.1.1 Silicon Area **1169**
15.1.2 Scaling Implications **1169**
15.1.3 Velocity Saturation **1171**
15.1.4 Subthreshold Conduction **1177**
15.1.5 Temperature, Voltage, and Process Variations **1178**
15.1.6 Wiring: The Interconnect **1178**
15.2 Digital IC Technologies, Logic-Circuit Families, and Design Methodologies **1179**
15.2.1 Digital IC Technologies and Logic-Circuit Families **1180**
15.2.2 Styles for Digital System Design **1182**
15.2.3 Design Abstraction and Computer Aids **1182**
15.3 Pseudo-NMOS Logic Circuits **1183**
15.3.1 The Pseudo-NMOS Inverter **1183**
15.3.2 Static Characteristics **1184**
15.3.3 Derivation of the VTC **1186**
15.3.4 Dynamic Operation **1188**
15.3.5 Design **1189**
15.3.6 Gate Circuits **1189**
15.3.7 Concluding Remarks **1190**
15.4 Pass-Transistor Logic Circuits **1192**
15.4.1 An Essential Design Requirement **1193**
15.4.2 Operation with NMOS Transistors as Switches **1194**
15.4.3 Restoring the Value of V_{OH} to V_{DD} **1198**
15.4.4 The Use of CMOS Transmission Gates as Switches **1199**
15.4.5 Examples of Pass-Transistor Logic Circuits **1206**
15.4.6 A Final Remark **1208**
15.5 Dynamic MOS Logic Circuits **1208**
15.5.1 The Basic Principle **1209**
15.5.2 Nonideal Effects **1212**
15.5.3 Domino CMOS Logic **1216**
15.5.4 Concluding Remarks **1217**
15.6 Bipolar and BiCMOS Logic Circuits **1217**
15.6.1 Emitter-Coupled Logic (ECL) **1218**
15.6.2 BiCMOS Digital Circuits **1223**
Summary **1226**
Problems **1227**

16 Memory Circuits 1236

Introduction **1237**
16.1 Latches and Flip-Flops **1238**
16.1.1 The Latch **1238**
16.1.2 The SR Flip-Flop **1240**
16.1.3 CMOS Implementation of SR Flip-Flops **1241**
16.1.4 A Simpler CMOS Implementation of the Clocked SR Flip-Flop **1247**
16.1.5 D Flip-Flop Circuits **1247**
16.2 Semiconductor Memories: Types and Architectures **1249**
16.2.1 Memory-Chip Organization **1250**
16.2.2 Memory-Chip Timing **1252**
16.3 Random-Access Memory (RAM) Cells **1253**
16.3.1 Static Memory (SRAM) Cell **1253**
16.3.2 Dynamic Memory (DRAM) Cell **1260**
16.4 Sense Amplifiers and Address Decoders **1262**
16.4.1 The Sense Amplifier **1263**

16.4.2 The Row-Address Decoder **1271**
16.4.3 The Column-Address Decoder **1273**
16.4.4 Pulse-Generation Circuits **1274**
16.5 Read-Only Memory (ROM) **1276**
16.5.1 A MOS ROM **1276**
16.5.2 Mask Programmable ROMs **1278**
16.5.3 Programmable ROMs (PROMs, EPROMs, and Flash) **1279**
16.6 CMOS Image Sensors **1281**
Summary **1282**
Problems **1283**

PART IV **FILTERS AND OSCILLATORS 1288**

17 Filters and Tuned Amplifiers 1290

Introduction **1291**
17.1 Filter Transmission, Types, and Specification **1292**
17.1.1 Filter Transmission **1292**
17.1.2 Filter Types **1293**
17.1.3 Filter Specification **1293**
17.2 The Filter Transfer Function **1296**
17.3 Butterworth and Chebyshev Filters **1300**
17.3.1 The Butterworth Filter **1300**
17.3.2 The Chebyshev Filter **1304**
17.4 First-Order and Second-Order Filter Functions **1307**
17.4.1 First-Order Filters **1308**
17.4.2 Second-Order Filter Functions **1311**
17.5 The Second-Order LCR Resonator **1316**
17.5.1 The Resonator Natural Modes **1316**
17.5.2 Realization of Transmission Zeros **1317**
17.5.3 Realization of the Low-Pass Function **1317**
17.5.4 Realization of the High-Pass Function **1319**
17.5.5 Realization of the Bandpass Function **1319**
17.5.6 Realization of the Notch Functions **1319**
17.5.7 Realization of the All-Pass Function **1321**
17.6 Second-Order Active Filters Based on Inductor Replacement **1322**
17.6.1 The Antoniou Inductance-Simulation Circuit **1322**
17.6.2 The Op Amp–RC Resonator **1323**
17.6.3 Realization of the Various Filter Types **1325**
17.6.4 The All-Pass Circuit **1325**
17.7 Second-Order Active Filters Based on the Two-Integrator-Loop Topology **1330**
17.7.1 Derivation of the Two-Integrator-Loop Biquad **1330**
17.7.2 Circuit Implementation **1332**
17.7.3 An Alternative Two-Integrator-Loop Biquad Circuit **1334**
17.7.4 Final Remarks **1335**
17.8 Single-Amplifier Biquadratic Active Filters **1336**
17.8.1 Synthesis of the Feedback Loop **1336**
17.8.2 Injecting the Input Signal **1339**
17.8.3 Generation of Equivalent Feedback Loops **1341**
17.9 Sensitivity **1344**
17.10 Transconductance-C Filters **1347**
17.10.1 Methods for IC Filter Implementation **1347**
17.10.2 Transconductors **1348**
17.10.3 Basic Building Blocks **1349**
17.10.4 Second-Order G_m–C Filter **1351**
17.11 Switched-Capacitor Filters **1354**
17.11.1 The Basic Principle **1354**
17.11.2 Practical Circuits **1356**
17.11.3 Final Remarks **1359**
17.12 Tuned Amplifiers **1359**
17.12.1 The Basic Principle **1360**
17.12.2 Inductor Losses **1362**
17.12.3 Use of Transformers **1363**
17.12.4 Amplifiers with Multiple Tuned Circuits **1365**
17.12.5 The Cascode and the CC–CB Cascade **1366**
17.12.6 Synchronous Tuning and Stagger Tuning **1367**
Summary **1368**
Problems **1369**

18 Signal Generators and Waveform-Shaping Circuits 1378

Introduction **1379**
18.1 Basic Principles of Sinusoidal Oscillators **1380**

18.1.1 The Oscillator Feedback Loop **1380**
18.1.2 The Oscillation Criterion **1381**
18.1.3 Analysis of Oscillator Circuits **1382**
18.1.4 Nonlinear Amplitude Control **1385**
18.1.5 A Popular Limiter Circuit for Amplitude Control **1386**
18.2 Op Amp–RC Oscillator Circuits **1388**
18.2.1 The Wien-Bridge Oscillator **1388**
18.2.2 The Phase-Shift Oscillator **1391**
18.2.3 The Quadrature Oscillator **1392**
18.2.4 The Active-Filter-Tuned Oscillator **1394**
18.2.5 A Final Remark **1396**
18.3 LC and Crystal Oscillators **1396**
18.3.1 The Colpitts and Hartley Oscillators **1396**
18.3.2 The Cross-Coupled LC Oscillator **1400**
18.3.3 Crystal Oscillators **1402**
18.4 Bistable Multivibrators **1404**
18.4.1 The Feedback Loop **1405**
18.4.2 Transfer Characteristic of the Bistable Circuit **1406**
18.4.3 Triggering the Bistable Circuit **1407**
18.4.4 The Bistable Circuit as a Memory Element **1407**
18.4.5 A Bistable Circuit with Noninverting Transfer Characteristic **1408**
18.4.6 Application of the Bistable Circuit as a Comparator **1409**
18.4.7 Making the Output Levels More Precise **1411**
18.5 Generation of Square and Triangular Waveforms Using Astable Multivibrators **1412**
18.5.1 Operation of the Astable Multivibrator **1413**
18.5.2 Generation of Triangular Waveforms **1415**
18.6 Generation of a Standardized Pulse: The Monostable Multivibrator **1417**
18.7 Integrated-Circuit Timers **1419**
18.7.1 The 555 Circuit **1419**
18.7.2 Implementing a Monostable Multivibrator Using the 555 IC **1420**
18.7.3 An Astable Multivibrator Using the 555 IC **1420**
18.8 Nonlinear Waveform-Shaping Circuits **1424**
18.8.1 The Breakpoint Method **1424**
18.8.2 The Nonlinear-Amplification Method **1426**
Summary **1428**
Problems **1428**

Appendices

A. VLSI Fabrication Technology (on website) A-1
B. SPICE Device Models and Design and Simulation Examples Using PSpice® and Multisim™ (on website) B-1
C. Two-Port Network Parameters (on website) C-1
D. Some Useful Network Theorems (on website) D-1
E. Single-Time-Constant Circuits (on website) E-1
F. s-Domain Analysis: Poles, Zeros, and Bode Plots (on website) F-1
G. Comparison of the MOSFET and the BJT (on website, also Table G.3 in text) G-1
H. Design of Stagger-Tuned Amplifiers (on website) H-1
I. Bibliography (on website) I-1
J. Standard Resistance Values and Unit Prefixes J-1
K. Typical Parameter Values for IC Devices Fabricated in CMOS and Bipolar Processes K-1
L. Answers to Selected Problems (on website) L-1

Index IN-1

TABLES

FOR REFERENCE AND STUDY

Table 1.1 The Four Amplifier Types 28
Table 1.2 Frequency Response of STC Networks 36
Table 2.1 Characteristics of the Ideal Op Amp 62
Table 3.1 Summary of Important Semiconductor Equations 169
Table 5.1 Regions of Operation of the NMOS Transistor 266
Table 5.2 Regions of Operation of the PMOS Transistor 275
Table 6.1 BJT Modes of Operation 307
Table 6.2 Summary of the BJT Current–Voltage Relationships in the Active Mode 322
Table 6.3 Simplified Models for the Operation of the BJT in DC Circuits 334
Table 7.1 Systematic Procedure for the Analysis of Transistor Amplifier Circuits 421
Table 7.2 Small-Signal Models of the MOSFET 421
Table 7.3 Small-Signal Models of the BJT 422
Table 7.4 Characteristics of MOSFET Amplifiers 452
Table 7.5 Characteristics of BJT Amplifiers 453
Table 8.1 Gain Distribution in the MOS Cascode Amplifier for Various Values of R_L 554
Table 10.1 The MOSFET High-Frequency Model 716
Table 10.2 The BJT High-Frequency Model 722
Table 11.1 Summary of the Parameters and Formulas for the Ideal Feedback-Amplifier Structure of Fig. 11.1 815
Table 11.2 Summary of Relationships for the Four Feedback-Amplifier Topologies 872
Table 13.1 DC Collector Currents of the 741 Circuit (μA) 1038
Table 14.1 Important Parameters of the VTC of the Logic Inverter 1102
Table 14.2 Summary of Important Characteristics of the CMOS Logic Inverter 1155
Table 15.1 Implications of Device and Voltage Scaling 1170
Table 15.2 Regions of Operation of the Pseudo-NMOS Inverter 1187
Table 17.1 Design Data for the Circuits Based on Inductance Simulation (Fig 17.22) 1328
Table 17.2 Design Data for the Tow-Thomas Biquad Circuit in Fig 17.26 1335
Table G.3 Comparison of the MOSFET and the BJT G-1
Table J.1 Standard Resistance Values J-1
Table J.2 SI Unit Prefixes J-2
Table J.3 Meter Conversion Factors J-2
Table K.1 Typical Values of CMOS Device Parameters K-1
Table K.2 Typical Parameter Values for BJTs K-1

"EXPAND-YOUR-PERSPECTIVE" NOTES

Chapter 1: Analog vs. Digital Circuit Engineers 15
Chapter 1: Bode Plots 37
Chapter 2: Integrated Instrumentation Amplifiers 85
Chapter 2: Early Op Amps and Analog Computation 88
Chapter 3: LCDs, the Face of Electronics 139
Chapter 4: The Earliest Semiconductor Diode 219
Chapter 4: From Indication to Illumination 229
Chapter 5: The First Field-Effect Devices 248
Chapter 5: Gordon Moore—His Law 288
Chapter 6: The Invention of the BJT 320
Chapter 7: Shockley and Silicon Valley 405
Chapter 7: Lee de Forest—a Father of the Electronics Age 454
Chapter 8: Solid Circuits with "Flying Wires" 511
Chapter 8: The Integrated Circuit 525
Chapter 9: The Long-Tailed Pair 612
Chapter 9: The International Solid-State Circuits Conference (ISSCC) 659
Chapter 10: John Milton Miller—Capacitance Multiplication 735
Chapter 10: RFID—Identification at a Distance 772
Chapter 11: Feedback—Historical Note 823
Chapter 11: Harry Nyquist—A Diverse Electronics Fundamentalist 875
Chapter 12: Early Power-Op-Amp Product 962
Chapter 12: Hans Camenzind—the Inventor of the Class D Amplifier 968
Chapter 13: The Genie of Analog 996
Chapter 13: The Creator of the μA741—David Fullagar 1031
Chapter 14: Frank Marion Wanless—the Inventor of CMOS 1117
Chapter 14: Federico Faggin—a Pioneer in Microprocessor Electronics 1141
Chapter 15: The Invisible Computer 1182
Chapter 15: Grand-Scale Graphics 1213
Chapter 16: Flip-Flop Fact 1240
Chapter 16: Blinding Flash 1282
Chapter 17: A Brief History of Analog Filters 1295
Chapter 17: Early Filter Pioneers—Cauer and Darlington 1348
Chapter 18: The Wien-Bridge Oscillator 1390
Chapter 18: Oscillator Pioneers 1400

PREFACE

Microelectronic Circuits, Seventh Edition, is intended as a text for the core courses in electronic circuits taught to majors in electrical and computer engineering. It should also prove useful to engineers and other professionals wishing to update their knowledge through self-study.

As was the case with the first six editions, the objective of this book is to develop in the reader the ability to analyze and design electronic circuits, both analog and digital, discrete and integrated. While the application of integrated circuits is covered, emphasis is placed on transistor circuit design. This is done because of our belief that even if the majority of those studying this book were not to pursue a career in IC design, knowledge of what is inside the IC package would enable intelligent and innovative application of such chips. Furthermore, with the advances in VLSI technology and design methodology, IC design itself has become accessible to an increasing number of engineers.

Prerequisites

The prerequisite for studying the material in this book is a first course in circuit analysis. As a review, some linear circuits material is included here in the appendices: specifically, two-port network parameters in Appendix C; some useful network theorems in Appendix D; single-time-constant circuits in Appendix E; and s-domain analysis in Appendix F. In addition, a number of relevant circuit analysis problems are included at the beginning of the end-of-chapter problems section of Chapter 1. No prior knowledge of physical electronics is assumed. All required semiconductor device physics is included, and Appendix A provides a brief description of IC fabrication. All these appendices can be found on the book's website.

Emphasis on Design

It has been our philosophy that circuit design is best taught by pointing out the various tradeoffs available in selecting a circuit configuration and in selecting component values for a given configuration. The emphasis on design has been retained in this edition. In addition to design examples, and design-oriented exercises and end-of-chapter problems (indicated with a D), the book includes on its website an extensive appendix (Appendix B) where a large number of simulation and design examples are presented. These emphasize the use of SPICE, the most valuable circuit-design aid.

New to the Seventh Edition

While maintaining the philosophy and pedagogical approach of the first six editions, several changes have been made to both organization and coverage. Our goal in making structural changes has been to increase modularity and thus flexibility for the instructor, without causing disturbance to courses currently using the sixth edition. Changes in coverage are necessitated by the continuing advances in technology which make some topics of greater relevance and others of less interest. As well, advances in IC process technology require that the numbers used in the examples, exercises and end-of-chapter problems be updated to reflect the parameters of newer generations of IC technologies (e.g., some problems utilize the parameters of the 65-nm CMOS process). This ensures that students are acquiring a real-world perspective on technology.

To improve presentation, a number of chapters and sections have been rewritten for greater clarity. Specific, noteworthy changes are:

1. **New End-of-Chapter Problems and a New Instructor's Solutions Manual.** The number of the end-of-chapter problems has increased by about 50. Of the resulting 1532 problems, 176 are entirely new and 790 have new data. The new Instructor's Solutions Manual is written by Adel Sedra.
2. **Expand-Your-Perspective Notes**. This is a new feature providing historical and application perspectives. About two such notes are included in each chapter. Most are focused on notable circuit engineers and key inventions.
3. **Greater Flexibility in Presenting the MOSFET and the BJT.** Two short and completely parallel chapters present the MOSFET (Chapter 5) and the BJT (Chapter 6). Here the focus is on the device structure and its physical operation, its current-voltage characteristics, and its application in dc circuits. The order of coverage of these two chapters is entirely at the instructor's discretion as they have been written to be completely independent of each other.
4. **A Unified Treatment of Transistor Amplifiers.** The heart of a first course in electronics is the study of transistor amplifiers. The seventh edition provides a new approach to this subject: A new Chapter 7 begins with the basic principles that underlie the operation of a transistor of either type as an amplifier, and presents such concepts as small-signal operation and modeling. This is followed by the classical configurations of transistor amplifiers, biasing methods, and practical discrete-circuit amplifiers. The combined presentation emphasizes the unity of the basic principles while allowing for separate treatment of the two device types where this is warranted. Very importantly, we are able to compare the two devices and to draw conclusions about their unique areas of application.
5. **Improved Presentation of Cascoding.** Chapter 8 dealing with the basic building blocks of IC amplifiers has been rewritten to improve presentation. Specifically, the development of cascoding and the key circuit building blocks, the cascode amplifier and the cascode current source, is now much clearer.
6. **Clearer and Simplified Study of Feedback.** The feedback chapter has been rewritten to improve, simplify and clarify the presentation of this key subject.
7. **Streamlined Presentation of Frequency Response.** While keeping the treatment of frequency response all together, the chapter has been rewritten to streamline its flow, and simplify and clarify the presentation.
8. **Updated Treatment of Output Stages and Power Amplifiers.** Here, we have updated the material on MOS power transistors and added a new section on the increasingly important class-D switching power amplifier.
9. **A More Contemporary Approach to Operational Amplifier Circuits.** While maintaining coverage of some of the enduring features and subcircuits of the classical 741 op amp, its total coverage is somewhat reduced to make room for modern IC op amp design techniques.

10. **Better Organized and Modernized Coverage of Digital IC Design**. Significant improvements have been made to the brief but comprehensive coverage of digital IC design in Part III. These include a better motivated study of CMOS logic circuits (Chapter 14) which now begins with logic gate circuits. The material on logic circuit technologies and design methodologies as well as the advanced topic of technology scaling and its implications have been moved to Chapter 15. This modularly structured chapter now deals with a selection of advanced and somewhat specialized topics. Since bipolar is hardly ever used in new digital design, coverage of ECL has been significantly reduced. Similarly, BiCMOS has become somewhat of a specialty topic and its coverage has been correspondingly reduced. Nevertheless, the complete material on both ECL and BiCMOS is now available on the book's website. Finally, we have added a new section on image sensors to Chapter 16 (Memory Circuits).
11. **Increased Emphasis on Integrated-Circuit Filters and Oscillators.** A section on a popular approach to integrated-circuit filter design, namely, Transconductance-C filters, has been added to Chapter 17. To make room for this new material, the subsection on stagger-tuned amplifiers has been removed and placed in Appendix H, on the website. The cross-coupled LC oscillator, popular in IC design, has been added to Chapter 18. The section on precision diode circuits has been removed but is still made available on the website.
12. **A Useful and Insightful Comparison of the MOSFET and the BJT.** This is now included in Appendix G, available on the website.

The Book's Website

A Companion Website for the book has been set up at www.oup.com/us/sedrasmith. Its content will change frequently to reflect new developments. The following material is available on the website:

1. Data sheets for hundreds of useful devices to help in laboratory experiments as well as in design projects.
2. Links to industrial and academic websites of interest.
3. A message center to communicate with the authors and with Oxford University Press.
4. Links to the student versions of both Cadence PSpice® and National Instruments Multisim™.
5. The input files for all the PSpice® and Multisim™ examples of Appendix B.
6. Step-by-step guidance to help with the simulation examples and the end-of-chapter problems identified with a SIM icon.
7. Bonus text material of specialized topics which are either not covered or covered briefly in the current edition of the textbook. These include:
   - Junction Field-Effect Transistors (JFETs)
   - Gallium Arsenide (GaAs) Devices and Circuits
   - Transistor-Transistor Logic (TTL) Circuits
   - Emitter-Coupled Logic (ECL) Circuits
   - BiCMOS Circuits
   - Precision Rectifier Circuits
8. Appendices for the Book:
   - Appendix A: VLSI Fabrication Technology
   - Appendix B: SPICE Device Models and Design and Simulation Examples Using PSpice® and Multisim™
   - Appendix C: Two-Port Network Parameters
   - Appendix D: Some Useful Network Theorems
   - Appendix E: Single-Time-Constant Circuits
   - Appendix F: *s*-domain Analysis: Poles, Zeros, and Bode Plots
   - Appendix G: Comparison of the MOSFET and the BJT

- Appendix H: Design of Stagger-Tuned Amplifiers
- Appendix I: Bibliography
- Appendix L: Answers to Selected Problems

Exercises and End-of-Chapter Problems

Over 475 Exercises are integrated throughout the text. The answer to each exercise is given below the exercise so students can check their understanding of the material as they read. Solving these exercises should enable the reader to gauge his or her grasp of the preceding material. In addition, more than 1530 end-of-chapter Problems, 65% of which are new or revised in this edition, are provided. The problems are keyed to the individual chapter sections and their degree of difficulty is indicated by a rating system: difficult problems are marked with an asterisk (*); more difficult problems with two asterisks (**); and very difficult (and/or time consuming) problems with three asterisks (***). We must admit, however, that this classification is by no means exact. Our rating no doubt depended to some degree on our thinking (and mood!) at the time a particular problem was created. Answers to sample problems are given in Appendix L (on the website), so students have a checkpoint to tell if they are working out the problems correctly. Complete solutions for all exercises and problems are included in the *Instructor's Solutions Manual*, which is available from the publisher to those instructors who adopt the book.

As in the previous six editions, many examples are included. The examples, and indeed most of the problems and exercises, are based on real circuits and anticipate the applications encountered in designing real-life circuits. This edition continues the use of numbered solution steps in the figures for many examples, as an attempt to recreate the dynamics of the classroom.

Course Organization

The book contains sufficient material for a sequence of two single-semester courses, each of 40-50 lecture hours. The modular organization of the book provides considerable flexibility for course design. In the following, we suggest content for a sequence of two classical or standard courses. We also describe some variations on the content of these two courses and specify supplemental material for a possible third course.

The First Course

The first course is based on Part I of the book, that is, Chapters 1–7. It can be taught, most simply by starting at the beginning of Chapter 1 and concluding with the end of Chapter 7. However, as guidance to instructors who wish to follow a different order of presentation or a somewhat modified coverage, or to deal with situations where time might be constrained, we offer the following remarks:

The core of the first course is the study of the two transistor types, Chapters 5 and 6, in whatever order the instructor wishes, and transistor amplifiers in Chapter 7. These three chapters must be covered in full.

Another important part of the first course is the study of diodes (Chapter 4). Here, however, if time does not permit, some of the applications in the later part of the chapter can be skipped.

We have found it highly motivational to cover op amps (Chapter 2) near the beginning of the course. This provides the students with the opportunity to work with a practical integrated circuit and to experiment with non-trivial circuits.

Coverage of Chapter 1, at least of the amplifier sections, should prove helpful. Here the sections on signals can be either covered in class or assigned as reading material. Section 1.6 on frequency response is needed if the frequency-response of op-amp circuits is to be studied; otherwise this section can be delayed to the second course.

Finally, if the students have not taken a course on physical electronics, Chapter 3 needs to be covered. Otherwise, it can be used as review material or skipped altogether.

The Second Course

The main subject of the second course is integrated-circuit amplifiers and is based on Part II of the book, that is, Chapters 8-13. Here also, the course can be taught most simply by beginning with Chapter 8 and concluding with Chapter 13. However, this being a second course, considerable flexibility in coverage is possible to satisfy particular curriculum designs and/or to deal with time constraints.

First, however, we note that the core material is presented in Chapters 8-11 and these four chapters must be covered, though not necessarily in their entirety. For instance, some of the sections near the end of a chapter and identified by the "advanced material" icon can be skipped, usually with no loss of continuity.

Beyond the required chapters, (8-11), the instructor has many possibilities for the remainder of the course. These include one or both of the two remaining chapters in Part II, namely, Output Stages and Power Amplifier (Chapter 12), and Op-Amp Circuits (Chapter 13).

Another possibility, is to include an introduction to digital integrated circuits by covering Chapter 14, and if time permits, selected topics of Chapters 15 and 16.

Yet another possibility for the remainder of the second course is selected topics from the filters chapter (17) and/or the oscillators chapter (18).

A Digitally Oriented First Course

A digitally-oriented first course can include the following: Chapter 1 (without Section 1.6), Chapter 2, Chapter 3 (if the students have not had any exposure to physical electronics), Chapter 4 (perhaps without some of the later applications sections), Chapter 5, selected topics from Chapter 7 emphasizing the basics of the application of the MOSFET as an amplifier, Chapter 14, and selected topics from Chapters 15 and 16. Such a course would be particularly suited for Computer Engineering students.

Supplemental Material/Third Course

Depending on the selection of topics for the first and second courses, some material will remain and can be used for part of a third course or as supplemental material to support student design projects. These can include Chapter 12 (Output Stages and Power Amplifiers), Chapter 13 (Op-Amp Circuits), Chapter 17 (Filters) and Chapter 18 (Oscillators), which can be used to support a third course on analog circuits. These can also include Chapters 14, 15 and 16 which can be used for a portion of a senior-level course on digital IC design.

The Accompanying Laboratory

Courses in electronic circuits are usually accompanied by laboratory experiments. To support the laboratory component for courses using this book, Professor Vincent Gaudet of the University of Waterloo has, in collaboration with K.C. Smith, authored a laboratory manual. *Laboratory Explorations*, together with an Instructor's Manual, is available from Oxford University Press.

Another innovative laboratory instruction system, designed to accompany this book, has been recently developed. Specifically, Illuster Technologies Inc. has developed a digitally controlled lab platform, AELabs. The platform is realized on printed circuit boards using surface mount devices. A wide variety of circuits can be configured on this platform through a custom graphical user interface. This allows students to conduct many experiments relatively quickly. More information is available from Illuster (see link on the Companion Website).

An Outline for the Reader

Part I, *Devices and Basic Circuits*, includes the most fundamental and essential topics for the study of electronic circuits. At the same time, it constitutes a complete package for a first course on the subject.

Chapter 1. The book starts with an introduction to the basic concepts of electronics in Chapter 1. Signals, their frequency spectra, and their analog and digital forms are presented. Amplifiers are introduced as circuit building blocks and their various types and models are studied. This chapter also establishes some of the terminology and conventions used throughout the text.

Chapter 2. Chapter 2 deals with operational amplifiers, their terminal characteristics, simple applications, and practical limitations. We chose to discuss the op amp as a circuit building block at this early stage simply because it is easy to deal with and because the student can experiment with op-amp circuits that perform nontrivial tasks with relative ease and with a sense of accomplishment. We have found this approach to be highly motivating to the student. We should point out, however, that part or all of this chapter can be skipped and studied at a later stage (for instance, in conjunction with Chapter 9, Chapter 11, and/or Chapter 13) with no loss of continuity.

Chapter 3. Chapter 3 provides an overview of semiconductor concepts at a level sufficient for understanding the operation of diodes and transistors in later chapters. Coverage of this material is useful in particular for students who have had no prior exposure to device physics. Even those with such a background would find a review of Chapter 3 beneficial as a refresher. The instructor can choose to cover this material in class or assign it for outside reading.

Chapter 4. The first electronic device, the diode, is studied in Chapter 4. The diode terminal characteristics, the circuit models that are used to represent it, and its circuit applications are presented. Depending on the time available in the course, some of the diode applications (e.g. Section 4.6) can be skipped. Also, the brief description of special diode types (Section 4.7) can be left for the student to read.

Chapters 5 and 6. The foundation of electronic circuits is established by the study of the two transistor types in use today: the MOS transistor in Chapter 5 and the bipolar transistor in Chapter 6. ***These two chapters have been written to be completely independent of one another and thus can be studied in either order, as desired.*** Furthermore, the two chapters have the same structure, making it easier and faster to study the second device, as well as to draw comparisons between the two device types.

Each of Chapters 5 and 6 begins with a study of the device structure and its physical operation, leading to a description of its terminal characteristics. Then, to allow the student to become very familiar with the operation of the transistor as a circuit element, a large number of examples are presented of dc circuits utilizing the device. The last section of each of Chapters 5 and 6 deals with second-order effects that are included for completeness, but that can be skipped if time does not permit detailed coverage.

Chapter 7. The heart of a first course in electronics is the study of transistor amplifiers. Chapter 7 (new to this edition) presents a unified treatment of the subject. It begins with the basic principles that underlie the operation of a transistor, of either type, as an amplifier, and proceeds to present the important concepts of small-signal operation and modeling. This is followed by a study of the basic configurations of single-transistor amplifiers. After a presentation of dc biasing methods, the chapter concludes with practical examples of discrete-circuit amplifiers. The combined presentation emphasizes the unity of the basic principles while allowing for separate treatment of the two device types where this is warranted. Very importantly, we are able to compare the two devices and to draw conclusions about their unique areas of application.

After the study of Part I, the reader will be fully prepared to study either integrated-circuit amplifiers in Part II, or digital integrated circuits in Part III.

Part II, *Integrated-Circuit Amplifiers*, is devoted to the study of practical amplifier circuits that can be fabricated in the integrated-circuit (IC) form. Its six chapters constitute a coherent treatment of IC amplifier design and can thus serve as a second course in electronic circuits.

MOS and Bipolar. Throughout Part II, both MOS and bipolar circuits are presented side-by-side. Because the MOSFET is by far the dominant device, its circuits are presented first. Bipolar circuits are discussed to the same depth but occasionally more briefly.

Chapter 8. Beginning with a brief introduction to the philosophy of IC design, Chapter 8 presents the basic circuit building blocks that are used in the design of IC amplifiers. These include current mirrors, current sources, gain cells, and cascode amplifiers.

Chapter 9. The most important IC building block, the differential pair, is the main topic of Chapter 9. The last section of Chapter 9 is devoted to the study of multistage amplifiers.

Chapter 10. Chapter 10 presents a comprehensive treatment of the important subject of amplifier frequency response. Here, Sections 10.1, 10.2, and 10.3 contain essential material; Section 10.4 provides an in-depth treatment of very useful new tools; and Sections 10.5 to 10.8 present the frequency response analysis of a variety of amplifier configurations that can be studied as and when needed. A selection of the latter sections can be made depending on the time available and the instructor's preference.

Chapter 11. The fourth of the essential topics of Part II, feedback, is the subject of Chapter 11. Both the theory of negative feedback and its application in the design of practical feedback amplifiers are presented. We also discuss the stability problem in feedback amplifiers and treat frequency compensation in some detail.

Chapter 12. In Chapter 12 we switch gears from dealing with small-signal amplifiers to those that are required to handle large signals and large amounts of power. Here we study the different amplifier classes—A, B, and AB—and their realization in bipolar and CMOS technologies. We also consider power BJTs and power MOSFETs, and study representative IC power amplifiers. A brief study of the increasingly popular Class D amplifier is also presented. Depending on the availability of time, some of the later sections can be skipped in a first reading.

Chapter 13. Finally, Chapter 13 brings together all the topics of Part II in an important application; namely, the design of operational amplifier circuits. We study both CMOS and bipolar op amps. In the latter category, besides the classical and still timely 741 circuit, we present modern techniques for the design of low-voltage op amps (Section 13.4).

Part III, *Digital Integrated Circuits*, provides a brief but nonetheless comprehensive and sufficiently detailed study of digital IC design. Our treatment is almost self-contained, requiring for the most part only a thorough understanding of the MOSFET material presented in Chapter 5. Thus, Part III can be studied right after Chapter 5. The only exceptions to this are the last section in Chapter 15 which requires knowledge of the BJT (Chapter 6). Also, knowledge of the MOSFET internal capacitances (Section 10.2.2) will be needed.

Chapter 14. Chapter 14 is the foundation of Part III. It begins with the motivating topic of CMOS logic-gate circuits. Then, following a detailed study of digital logic inverters, we concentrate on the CMOS inverter; its static and dynamic characteristics and its design. Transistor sizing and power dissipation round out the topics of Chapter 14. The material covered in this chapter is the minimum needed to learn something meaningful about digital circuits.

Chapter 15. Chapter 15 has a modular structure and presents six topics of somewhat advanced nature. It begins with a presentation of Moore's law and the technology scaling that has made the multi-billion-transistor chip possible. This is followed by an overview of digital IC technologies, and the design methodologies that make the design of super-complex digital ICs possible. Four different logic-circuit types are then presented. Only the last of these includes bipolar transistors.

Chapter 16. Digital circuits can be broadly divided into logic and memory circuits. The latter is the subject of Chapter 16.

Part IV, *Filters and Oscillators*, is intentionally oriented toward applications and systems. The two topics illustrate powerfully and dramatically the application of both negative and positive feedback.

Chapter 17. Chapter 17 deals with the design of filters, which are important building blocks of communication and instrumentation systems. A comprehensive, design-oriented treatment of the subject is presented. The material provided should allow the reader to perform a complete filter design, starting from specification and ending with a complete circuit realization. A wealth of design tables is included.

Chapter 18. Chapter 18 deals with circuits for the generation of signals with a variety of waveforms: sinusoidal, square, and triangular. We also present circuits for the nonlinear shaping of waveforms.

Appendices. The twelve appendices contain much useful background and supplementary material. We wish to draw the reader's attention in particular to the first two: Appendix A provides a concise introduction to the important topic of IC fabrication technology including IC layout. Appendix B provides SPICE device models as well as a large number of design and simulation examples in PSpice® and Multisim™. The examples are keyed to the book chapters. These Appendices and a great deal more material on these simulation examples can be found on the Companion Website.

Ancillaries

A complete set of ancillary materials is available with this text to support your course.

For the Instructor

The Ancillary Resource Center (ARC) at www.oup-arc.com/sedrasmith is a convenient destination for all the instructor resources that accompany *Microelectronic Circuits*. Accessed online through individual user accounts, the ARC provides instructors with access to up-to-date ancillaries at any time while guaranteeing the security of grade-significant resources. The ARC replaces the Instructor's Resource CD that accompanied the sixth edition. On the ARC, you will find:

- **An electronic version of the Instructor's Solutions Manual.**
- **PowerPoint-based figure slides** that feature all the images and summary tables from the text, with their captions, so they can easily be displayed and explained in class.
- Detailed **instructor's support** for the SPICE circuit simulations in Multisim™ and PSpice®.

The **Instructor's Solutions Manual** (ISBN 978-0-19-933915-0), written by Adel Sedra, contains detailed solutions to all in-text exercises and end-of-chapter problems found in *Microelectronic Circuits*. The Instructor's Solutions Manual for ***Laboratory Explorations to Accompany Microelectronic Circuits*** (ISBN 978-0-19-933926-6) contains detailed solutions to all the exercises and problems found in this student's laboratory guide.

For the Student and Instructor

A Companion Website at www.oup.com/us/sedrasmith features permanently cached versions of device datasheets, so students can design their own circuits in class. The website also contains SPICE circuit simulation examples and lessons. Bonus text topics and the Appendices are also featured on the website.

The ***Laboratory Explorations to Accompany Microelectronic Circuits*** (ISBN 978-0-19-933925-9) invites students to explore the realm of real-world engineering through practical, hands-on experiments. Keyed to sections in the text and taking a "learn-by-doing" approach, it presents labs that focus on the development of practical engineering skills and design practices.

Acknowledgments

Many of the changes in this seventh edition were made in response to feedback received from instructors who adopted the sixth edition. We are grateful to all those who took the time to write to us. In addition, many of the reviewers provided detailed commentary on the sixth edition and suggested a number of the changes that we have incorporated in this edition. They are listed later; to all of them, we extend our sincere thanks. Adel Sedra is also grateful for the feedback received from the students who have taken his electronics courses over the past number of years at the University of Waterloo.

A number of individuals made significant contributions to this edition. Vincent Gaudet of the University of Waterloo contributed to Part III as well as co-authoring the laboratory manual. Wai-Tung Ng of the University of Toronto contributed to Chapter 12 and updated Appendix A (of which he is the original author). Muhammad Faisal of the University of Michigan updated Appendix B, which he helped create for the sixth edition; helped in obtaining the cover photo, and has over a number of years been the source of many good ideas. Olivier Trescases and his students at the University of Toronto pioneered the laboratory system described elsewhere in the Preface. Jennifer Rodrigues typed all the revisions, as she did for a number of the previous editions, with tremendous skill and good humour. Chris Schroeder was of great assistance to Adel Sedra with local logistics. Laura Fujino assisted in many ways and in particular with the "Expand-Your-Perspective" notes. To all of these friends and colleagues we say thank you.

Over the recent years we have benefited greatly from discussions with a number of colleagues and friends. In particular we are very grateful to the following: James Barby, University of Waterloo; David Nairn, University of Waterloo; Anthony Chan Carusone, University of Toronto; David Johns, University of Toronto; Ken Martin, University of Toronto; Khoman Phang, University of Toronto; Gordon Roberts, McGill University; Ali Sheikholeslami, University of Toronto; and Amir Yazdani, Ryerson University.

The cover photograph shows a 3D IC system, which demonstrates the concept of wireless power delivery and communication through multiple layers of CMOS chips. The communication circuits were demonstrated in an IBM 45 nm SOI CMOS process. This technology is designed to serve a multi-Gb/s interconnect between cores spread across several IC layers for high-performance processors. We are grateful to Professor David Wentzloff, Director of the Wireless Integrated Circuits Group at the University of Michigan, who allowed us to use this image, and to Muhammad Faisal, Founder of Movellus Circuits Incorporated, who edited the image.

A large number of people at Oxford University Press contributed to the development of this edition and its various ancillaries. We would like to specifically mention Marketing Manager David Jurman, Marketing Director Frank Mortimer, Higher Ed Sales Director Bill Marting, Copywriter Kristin Maffei, Art Director Michele Laseau, Production Manager Lisa Grzan, Team Leader Amy Whitmer, and Senior Production Editor Jane Lee.

We wish to extend special thanks to our Publisher at Oxford University Press, John Challice, and the Editorial Director, Patrick Lynch. Both have always shown great interest in this book and have provided considerable guidance and support throughout the process of preparing this edition. The Senior Acquisitions Editor, Nancy Blaine, and Associate Editor, Christine Mahon, have done a truly outstanding job. It has been a pleasure to work with both of them, both as professionals and as highly thoughtful individuals; we owe them much gratitude. On the production side, Barbara Mathieu, Senior Production Editor, has been superb: her attention to detail and emphasis on quality is without par.

Finally, we wish to thank our families for their support and understanding, and to thank all the students and instructors who have valued this book throughout its history.

Adel S. Sedra
Kenneth C. (KC) Smith
Waterloo, Ontario, Canada
August 2014

Reviewers of Seventh Edition

Junseok Chae, Arizona State University, Tempe, AZ
Liang Dong, Baylor University, Waco, TX
Muhammad Faisal, University of Michigan, Ann Arbor, MI
Patrick Fay, University of Notre Dame, Notre Dame, IN
Vincent Gaudet, University of Waterloo, Waterloo, Canada
Elmer A Grubbs, Northern Arizona University, Flagstaff, AZ
Serhiy Levkov, New Jersey Institute of Technology, Newark, NJ
Leda Lunardi, North Carolina State University, Raleigh, NC
Phyllis R. Nelson, California State Polytechnic University, Pomona, CA
Robert W. Newcomb, University of Maryland, College Park, MD
Toshikazu Nishida, University of Florida, Gainesville, FL
Matthew Swabey, Purdue University, West Lafayette, IN
Khalid Hasan Tantawi, University of Alabama, Huntsville, AL
Farid M. Tranjan, University of North Carolina, Charlotte, NC
Mustapha C.E. Yagoub, University of Ottawa, Ottawa, Canada
Justin Jackson, Weber State University, Ogden, UT
John Mankowski, Texas Tech University, Lubbock, TX
Chris Mi, University of Michigan, Dearborn, MI

Reviewers of Prior Editions

Maurice Aburdene, Bucknell University, Lewisburg, PA
Michael Bartz, University of Memphis, TN
Elizabeth Brauer, Northern Arizona University, Flagstaff, AZ
Martin Brooke, Duke University, Durham, NC
Patrick L. Chapman, University of Illinois, Urbana–Champaign, IL
Yun Chiu, University of Illinois, Urbana–Champaign, IL
Roy H. Cornely, New Jersey Institute of Technology, Newark, NJ
Norman Cox, Missouri University of Science and Technology, Rolla, MO
Dale L. Critchlow, University of Vermont, Burlingon, VT
Robert Bruce Darling, University of Washington, Seattle, WA
Artice Davis, San Jose State University, CA
John Davis, University of Texas, Austin, TX
Christopher DeMarco, University of Wisconsin, Madison, WI
Robert Engelken, Arkansas State University, Jonesboro, AR
Ethan Farquhar, University of Tennessee, Knoxville, TN
Eby G. Friedman, University of Rochester, NY
Paul M. Furth, New Mexico State University, Las Cruces, NM
Rhett T. George, Jr., Duke University, Durham, NC
Roobik Gharabagi, St. Louis University, MO
George Giakos, University of Akron, OH
John Gilmer, Wilkes University, Wilkes-Barre, PA
Michael Green, University of California, Irvine, CA
Steven de Haas, California State University, Sacramento, CA
Anas Hamoui, McGill University, Montreal, Canada
Reza Hashemian, Northern Illinois University, DeKalb, IL
William Harrell, Clemson University, SC
Reid Harrison, University of Utah, Salt Lake City, UT
Ward J. Helms, University of Washington, Seattle, WA
Richard Hornsey, York University, Toronto, Canada
Timothy Horiuchi, University of Maryland, College Park, MD
Hsiung Hsu, The Ohio State University, Columbus, OH
Robert Irvine, California State Polytechnic University, Pomona, CA
Mohammed Ismail, The Ohio State University, Columbus, OH
Paul Israelsen, Utah State University, Logan UT
Steve Jantzi, Broadcom, CA
Zhenhua Jiang, University of Miami, FL
Marian Kazimierczuk, Wright State University, Dayton, OH
John Khoury, Columbia University, New York, NY
Jacob B. Khurgin, The Johns Hopkins University, Baltimore, MD
Seongsin M. Kim, University of Alabama, Tuscaloosa, AL
Roger King, University of Toledo, OH
Clark Kinnaird, Southern Methodist University, Dallas, TX
Robert J. Krueger, University of Wisconsin, Milwaukee, WI
Joy Laskar, Georgia Institute of Technology, Atlanta, GA
Tsu-Jae King Liu, University of California, Berkeley, CA
Yicheng Lu, Rutgers University, Piscataway, NJ
David Luke, University of New Brunswick, Fredericton, Canada
Thomas Matthews, California State University, Sacramento, CA
Un-Ku Moon, Oregon State University, Corvallis, OR
Bahram Nabet, Drexel University, Philadelphia, PA
Dipankar Nagchoudhuri, Indian Institute of Technology, Delhi, India
David Nairn, University of Waterloo, Waterloo, Canada
Joseph H. Nevin, University of Cincinnati, OH
Ken Noren, University of Idaho, Moscow, ID
Brita Olson, California Polytechnic University, Pomona, CA
Martin Peckerar, University of Maryland, College Park, MD
Khoman Phang, University of Toronto, Canada
Mahmudur Rahman, Santa Clara University, CA
Rabin Raut, Concordia University, Montreal, Canada
John A. Ringo, Washington State University, Pullman, WA
Zvi S. Roth, Florida Atlantic University, Boca Raton, FL
Mulukutla Sarma, Northeastern University, Boston, MA
John Scalzo, Louisiana State University, Baton Rouge, LA
Norman Scheinberg, City College, New York, NY
Pierre Schmidt, Florida International University, Miami, FL
Richard Schreier, Analog Devices, Toronto, Canada
Dipankar Sengupta, Royal Melbourne Institute of Technology, Australia
Ali Sheikholeslami, University of Toronto, Canada
Kuang Sheng, Rutgers University, Piscataway, NJ
Michael L. Simpson, University of Tennessee, Knoxville, TN
Karl A. Spuhl, Washington University in St. Louis, MO
Charles Sullivan, Dartmouth College, Hanover, NH
Andrew Szeto, San Diego State University, CA
Joel Therrien, University of Massachusetts, Lowell, MA
Len Trombetta, University of Houston, TX
Daniel van der Weide, University of Delaware, Newark, DE
Gregory M. Wierzba, Michigan State University, East Lansing, MI
Donna Yu, North Carolina State University, Raleigh, NC
Jiann-Shiun Yuan, University of Central Florida, Orlando, FL
Sandra Yost, University of Detroit, Mercy, MI
Alex Zaslavsky, Brown University, Providence, RI
Jianhua (David) Zhang, University of Illinois, Urbana–Champaign, IL

Microelectronic Circuits

PART I

Devices and Basic Circuits

CHAPTER 1
Signals and Amplifiers 4

CHAPTER 2
Operational Amplifiers 58

CHAPTER 3
Semiconductors 134

CHAPTER 4
Diodes 174

CHAPTER 5
MOS Field-Effect Transistors (MOSFETs) 246

CHAPTER 6
Bipolar Junction Transistors (BJTs) 304

CHAPTER 7
Transistor Amplifiers 366

Part I, *Devices and Basic Circuits*, includes the most fundamental and essential topics for the study of electronic circuits. At the same time, it constitutes a complete package for a first course on the subject.

The heart of Part I is the study of the three basic semiconductor devices: the diode (Chapter 4), the MOS transistor (Chapter 5), and the bipolar transistor (Chapter 6). In each case, we study the device operation, its characterization, and its basic circuit applications. Chapter 7 then follows with a study of the most fundamental application of the two transistor types; namely, their use in amplifier design. This side-by-side study of MOSFET and BJT amplifiers allows us to see similarities between these amplifiers and to compare them, which in turn highlights the distinct areas of applicability of each, as well as showing the unity of the basic principles that underlie the use of transistors as amplifiers.

For those who have not had a prior course on device physics, Chapter 3 provides an overview of semiconductor concepts at a level sufficient for the study of electronic circuits. A review of Chapter 3 should prove useful even for those with prior knowledge of semiconductors.

Since the purpose of electronic circuits is the processing of signals, it is essential to understand signals, their characterization in the time and frequency domains, and their analog and digital representations. The basis for such understanding is provided in Chapter 1, which also introduces the most common signal-processing function, *amplification*, and the characterization and types of *amplifiers*.

Besides diodes and transistors, the basic electronic devices, the op amp is studied in Part I. Although not an electronic device in the most fundamental sense, the op amp is commercially available as an integrated circuit (IC) package and has well-defined terminal characteristics. Thus, even though the op amp's internal circuit is complex, typically incorporating 20 or more transistors, its almost-ideal terminal behavior makes it possible to treat the op amp as a circuit element and to use it in the design of powerful circuits, as we do in Chapter 2, without any knowledge of its internal construction. We should mention, however, that the study of op amps can be delayed until a later point, and Chapter 2 can be skipped with no loss of continuity.

The foundation of this book, and of any electronics course, is the study of the two transistor types in use today: the MOS transistor in Chapter 5 and the bipolar transistor in Chapter 6. These two chapters have been written to be completely independent of each other and thus can be studied in either order, as desired.

After the study of Part I, the reader will be fully prepared to undertake the study of either integrated-circuit amplifiers in Part II or digital integrated circuits in Part III.

CHAPTER 1

Signals and Amplifiers

Introduction 5

1.1 Signals 6

1.2 Frequency Spectrum of Signals 9

1.3 Analog and Digital Signals 12

1.4 Amplifiers 15

1.5 Circuit Models for Amplifiers 23

1.6 Frequency Response of Amplifiers 33

Summary 44

Problems 45

IN THIS CHAPTER YOU WILL LEARN

1. That electronic circuits process signals, and thus understanding electrical signals is essential to appreciating the material in this book.
2. The Thévenin and Norton representations of signal sources.
3. The representation of a signal as the sum of sine waves.
4. The analog and digital representations of a signal.
5. The most basic and pervasive signal-processing function: signal amplification, and correspondingly, the signal amplifier.
6. How amplifiers are characterized (modeled) as circuit building blocks independent of their internal circuitry.
7. How the frequency response of an amplifier is measured, and how it is calculated, especially in the simple but common case of a single-time-constant (STC) type response.

Introduction

The subject of this book is modern electronics, a field that has come to be known as **microelectronics**. **Microelectronics** refers to the integrated-circuit (IC) technology that at the time of this writing is capable of producing circuits that contain billions of components in a small piece of silicon (known as a **silicon chip**) whose area is on the order of 100 mm^2. One such microelectronic circuit, for example, is a complete digital computer, which accordingly is known as a **microcomputer** or, more generally, a **microprocessor**. The microelectronic circuits you will learn to design in this book are used in almost every device we encounter in our daily lives: in the appliances we use in our homes; in the vehicles and transportation systems we use to travel; in the cell phones we use to communicate; in the medical equipment we need to care for our health; in the computers we use to do our work; and in the audio and video systems, the radio and TV sets, and the multitude of other digital devices we use to entertain ourselves. Indeed, it is difficult to conceive of modern life without microelectronic circuits.

In this book we shall study electronic devices that can be used singly (in the design of **discrete circuits**) or as components of an **integrated-circuit (IC)** chip. We shall study the design and analysis of interconnections of these devices, which form discrete and integrated

circuits of varying complexity and perform a wide variety of functions. We shall also learn about available IC chips and their application in the design of electronic systems.

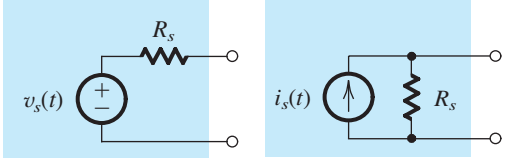
The purpose of this first chapter is to introduce some basic concepts and terminology. In particular, we shall learn about signals and about one of the most important signal-processing functions electronic circuits are designed to perform, namely, signal amplification. We shall then look at circuit representations or models for linear amplifiers. These models will be employed in subsequent chapters in the design and analysis of actual amplifier circuits.

In addition to motivating the study of electronics, this chapter serves as a bridge between the study of linear circuits and that of the subject of this book: the design and analysis of electronic circuits.

1.1 Signals

Signals contain information about a variety of things and activities in our physical world. Examples abound: Information about the weather is contained in signals that represent the air temperature, pressure, wind speed, etc. The voice of a radio announcer reading the news into a microphone provides an acoustic signal that contains information about world affairs. To monitor the status of a nuclear reactor, instruments are used to measure a multitude of relevant parameters, each instrument producing a signal.

To extract required information from a set of signals, the observer (be it a human or a machine) invariably needs to **process** the signals in some predetermined manner. This **signal processing** is usually most conveniently performed by electronic systems. For this to be possible, however, the signal must first be converted into an electrical signal, that is, a voltage or a current. This process is accomplished by devices known as **transducers**. A variety of transducers exist, each suitable for one of the various forms of physical signals. For instance, the sound waves generated by a human can be converted into electrical signals by using a microphone, which is in effect a pressure transducer. It is not our purpose here to study transducers; rather, we shall assume that the signals of interest already exist in the electrical domain and represent them by one of the two equivalent forms shown in Fig. 1.1. In Fig. 1.1(a) the signal is represented by a voltage source $v_s(t)$ having a source resistance R_s. In the alternate representation of Fig. 1.1(b) the signal is represented by a current source $i_s(t)$ having a source resistance R_s. Although the two representations are equivalent, that in Fig. 1.1(a) (known as the Thévenin form) is preferred when R_s is low. The representation of Fig. 1.1(b) (known as the Norton form) is preferred when R_s is high. The reader will come to appreciate this point later in this chapter when we study the different types of amplifiers. For the time being, it is important to be familiar with Thévenin's and Norton's theorems (for a



(a) (b)

Figure 1.1 Two alternative representations of a signal source: **(a)** the Thévenin form; **(b)** the Norton form.

brief review, see Appendix D) and to note that for the two representations in Fig. 1.1 to be equivalent, their parameters are related by

$$v_s(t) = R_s i_s(t)$$

Example 1.1

The output resistance of a signal source, although inevitable, is an imperfection that limits the ability of the source to deliver its full signal strength to a **load**. To see this point more clearly, consider the signal source when connected to a load resistance R_L as shown in Fig. 1.2. For the case in which the source is represented by its Thévenin equivalent form, find the voltage v_o that appears across R_L, and hence the condition that R_s must satisfy for v_o to be close to the value of v_s. Repeat for the Norton-represented source; in this case finding the current i_o that flows through R_L and hence the condition that R_s must satisfy for i_o to be close to the value of i_s.

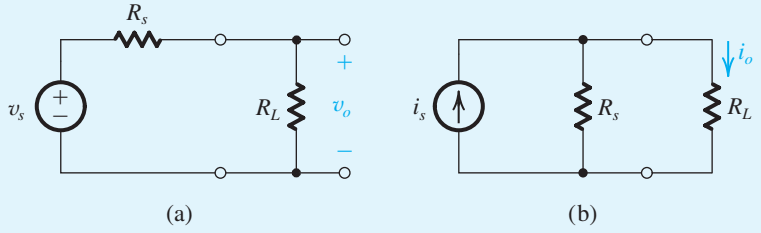


Figure 1.2 Circuits for Example 1.1.

Solution

For the Thévenin-represented signal source shown in Fig. 1.2(a), the output voltage v_o that appears across the load resistance R_L can be found from the ratio of the voltage divider formed by R_s and R_L,

$$v_o = v_s \frac{R_L}{R_L + R_s}$$

From this equation we see that for

$$v_o \simeq v_s$$

the source resistance R_s must be much lower than the load resistance R_L,

$$R_s \ll R_L$$

Thus, for a source represented by its Thévenin equivalent, ideally $R_s = 0$, and as R_s is increased, relative to the load resistance R_L with which this source is intended to operate, the voltage v_o that appears across the load becomes smaller, not a desirable outcome.

Example 1.1 *continued*

Next, we consider the Norton-represented signal source in Fig. 1.2(b). To obtain the current i_o that flows through the load resistance R_L, we utilize the ratio of the current divider formed by R_s and R_L,

$$i_o = i_s \frac{R_s}{R_s + R_L}$$

From this relationship we see that for

$$i_o \simeq i_s$$

the source resistance R_s must be much larger than R_L,

$$R_s \gg R_L$$

Thus for a signal source represented by its Norton equivalent, ideally $R_s = \infty$, and as R_s is reduced, relative to the load resistance R_L with which this source is intended to operate, the current i_o that flows through the load becomes smaller, not a desirable outcome.

Finally, we note that although circuit designers cannot usually do much about the value of R_s, they may have to devise a circuit solution that minimizes or eliminates the loss of signal strength that results when the source is connected to the load.

EXERCISES

1.1 For the signal-source representations shown in Figs. 1.1(a) and 1.1(b), what are the open-circuit output voltages that would be observed? If, for each, the output terminals are short-circuited (i.e., wired together), what current would flow? For the representations to be equivalent, what must the relationship be between v_s, i_s, and R_s?
Ans. For (a), $v_{oc} = v_s(t)$; for (b), $v_{oc} = R_s i_s(t)$; for (a), $i_{sc} = v_s(t)/R_s$; for (b), $i_{sc} = i_s(t)$; for equivalency, $v_s(t) = R_s i_s(t)$

1.2 A signal source has an open-circuit voltage of 10 mV and a short-circuit current of 10 μA. What is the source resistance?
Ans. 1 kΩ

1.3 A signal source that is most conveniently represented by its Thévenin equivalent has $v_s = 10$ mV and $R_s = 1$ kΩ. If the source feeds a load resistance R_L, find the voltage v_o that appears across the load for $R_L = 100$ kΩ, 10 kΩ, 1 kΩ, and 100 Ω. Also, find the lowest permissible value of R_L for which the output voltage is at least 80% of the source voltage.
Ans. 9.9 mV; 9.1 mV; 5 mV; 0.9 mV; 4 kΩ

1.4 A signal source that is most conveniently represented by its Norton equivalent form has $i_s = 10$ μA and $R_s = 100$ kΩ. If the source feeds a load resistance R_L, find the current i_o that flows through the load for $R_L = 1$ kΩ, 10 kΩ, 100 kΩ, and 1 MΩ. Also, find the largest permissible value of R_L for which the load current is at least 80% of the source current.
Ans. 9.9 μA; 9.1 μA; 5 μA; 0.9 μA; 25 kΩ

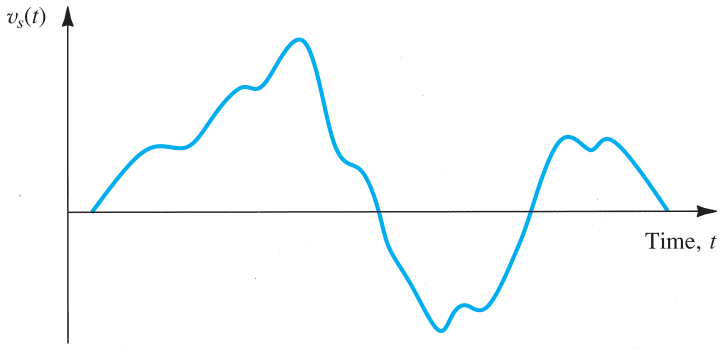


Figure 1.3 An arbitrary voltage signal $v_s(t)$.

From the discussion above, it should be apparent that a signal is a time-varying quantity that can be represented by a graph such as that shown in Fig. 1.3. In fact, the information content of the signal is represented by the changes in its magnitude as time progresses; that is, the information is contained in the "wiggles" in the signal waveform. In general, such waveforms are difficult to characterize mathematically. In other words, it is not easy to describe succinctly an arbitrary-looking waveform such as that of Fig. 1.3. Of course, such a description is of great importance for the purpose of designing appropriate signal-processing circuits that perform desired functions on the given signal. An effective approach to signal characterization is studied in the next section.

1.2 Frequency Spectrum of Signals

An extremely useful characterization of a signal, and for that matter of any arbitrary function of time, is in terms of its **frequency spectrum**. Such a description of signals is obtained through the mathematical tools of **Fourier series** and **Fourier transform**.[1] We are not interested here in the details of these transformations; suffice it to say that they provide the means for representing a voltage signal $v_s(t)$ or a current signal $i_s(t)$ as the sum of sine-wave signals of different frequencies and amplitudes. This makes the sine wave a very important signal in the analysis, design, and testing of electronic circuits. Therefore, we shall briefly review the properties of the sinusoid.

Figure 1.4 shows a sine-wave voltage signal $v_a(t)$,

$$v_a(t) = V_a \sin \omega t \tag{1.1}$$

where V_a denotes the peak value or amplitude in volts and ω denotes the angular frequency in radians per second; that is, $\omega = 2\pi f$ rad/s, where f is the frequency in hertz, $f = 1/T$ Hz, and T is the period in seconds.

The sine-wave signal is completely characterized by its peak value V_a, its frequency ω, and its phase with respect to an arbitrary reference time. In the case depicted in Fig. 1.4, the time

[1]The reader who has not yet studied these topics should not be alarmed. No detailed application of this material will be made until Chapter 10. Nevertheless, a general understanding of Section 1.2 should be very helpful in studying early parts of this book.