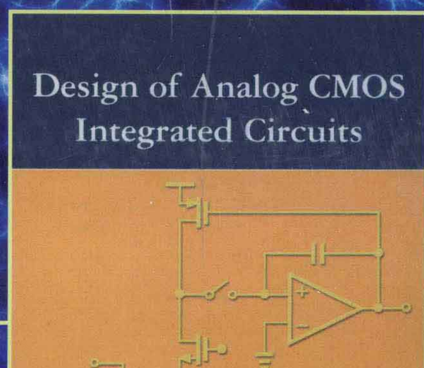
国外电子电气经典教材系列

模拟CMOS集成电路设计

(英文版)

Design of Analog CMOS Integrated Circuits

[美] Behzad Razavi 著 王志华 注释



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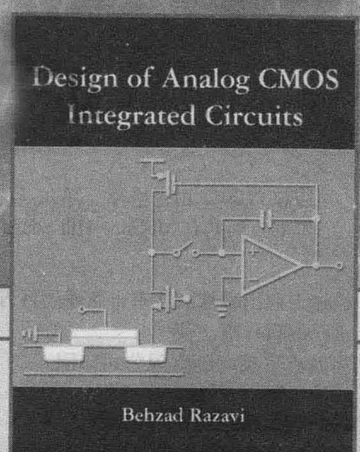

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图书在版编目（CIP）数据

模拟CMOS集成电路设计（英文版）/（美）拉扎维（Razavi, B.）著；王志华注释. —北京：机械工业出版社，2013.7
（国外电子电气经典教材系列）
书名原文：Design of Analog CMOS Integrated Circuits

ISBN 978-7-111-43027-8

I. 模… II. ① 拉… ② 王… III. CMOS电路－电路设计－教材－英文 IV. TN432.02

中国版本图书馆CIP数据核字（2013）第136419号

本书版权登记号：图字：01-2013-1650

机械工业出版社（北京市西城区百万庄大街22号 邮政编码 100037）
责任编辑：李 荣
藁城市京瑞印刷有限公司印刷
2013年7月第1版第1次印刷
150mm×214mm · 21.875印张
标准书号：ISBN 978-7-111-43027-8
定 价：79.00元

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出版者的话

文艺复兴以降，源远流长的科学精神和逐步形成的学术规范，使西方国家在自然科学的各个领域取得了垄断性的优势；也正是这样的传统，使美国在信息技术发展的六十多年间名家辈出、独领风骚。在商业化的进程中，美国的产业界与教育界越来越紧密地结合，信息学科中的许多泰山北斗同时身处科研和教学的最前线，由此而产生的经典科学著作，不仅擘划了研究的范畴，还揭示了学术的源变，既遵循学术规范，又自有学者个性，其价值并不会因年月的流逝而减退。

近年，在全球信息化大潮的推动下，我国的信息产业发展迅猛，对专业人才的需求日益迫切。这对我国教育界和出版界都既是机遇，也是挑战；而专业教材的建设在教育战略上显得举足轻重。在我国信息技术发展时间较短的现状下，美国等发达国家在其信息科学发展的几十年间积淀和发展的经典教材仍有许多值得借鉴之处。因此，引进一批国外优秀教材将对我国教育事业的发展起到积极的推动作用，也是与世界接轨、建设真正的世界一流大学的必由之路。

机械工业出版社华章公司较早意识到“出版要为教育服务”。自 1998 年开始，我们就将工作重点放在了遴选、移译国外优秀教材上。经过多年的不懈努力，我们与 Pearson，McGraw-Hill，John Wiley & Sons，Elsevier，Cambridge 等世界著名出版公司建立了良好的合作关系，从他们现有的数百种教材中甄选出《Digital Design: Principles and Practices，4E（数字设计原理与实践，原书第 4 版）》(John F.Wakerly 著）、《Fundamentals of Digital Logic with Verilog Design（数字逻辑基础与 Verilog 设计）》（Stephen Brown 著）、《Electromagnetic Field Theory Fundamentals，2E（电磁场与电磁波，原书第 2 版）》（Bhag Singh Guru 著）、《Fundamentals of Electric Circuits，5E(电路基础，原书第 5 版、英文版第 5 版)》（Charles K. Alexander 著）、《Digital Fundamentals: A Systems Approach（数字基础：系统方法)》（Thomas L. Floyd 著）、《Introductory Circuit Analysis, 12E（电路分析导论，原书第 12 版，本科教学版)》（Robert L.Boylestad 著）、《Foundations of MEMS，2E(微机电系统基础（原书第 2 版)》（Chang Liu 著）等大师名家的经典教材，以“国外电子电气经典教材系列”为总称出

版，供读者学习、研究及珍藏。

权威的作者、经典的教材、一流的译者、严格的审校、精细的编辑，这些因素使我们的图书有了质量的保证。随着电子电气专业学科建设的不断完善和教材改革的逐渐深化，教育界对国外电子电气教材的需求和应用都将步入一个新的阶段，我们的目标是尽善尽美，而反馈的意见正是我们达到这一终极目标的重要帮助。华章公司欢迎老师和读者对我们的工作提出建议或给予指正，我们的联系方法如下：

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写在注释之前的话

20 世纪 80 年代初，随着集成电路制造工艺的进步，以及计算技术、数字信号处理和处理器技术的提高，人们期望更多的信号处理能够从模拟域转移到数字域，甚至预言当集成电路的规模和处理速度足够大之后，所有的信号处理都可以通过数字化来实现，模拟信号处理将成为历史，模拟信号处理所使用的模拟电路将走向消亡。然而 30 多年过去了，工业界对模拟电路的需求不但没有减少，反而日益增加；模拟电路设计逐渐成为系统芯片（SoC）设计的瓶颈。究其原因，不单由于物理世界的本质是模拟的，从物理世界获取的信息源一定是模拟的；不单由于人们的感官本质是模拟的，信号处理的目的是为人们能够感知，因此提供给人类的信号应该是模拟的；也不单由于技术上采用数字电路完全取代相应的模拟电路的功能仍然非常困难甚至是不可能的；更重要的是随着数字集成技术的提高，移动计算及移动应用的普及，客观上更需要将模拟电路和数字处理集成为 SoC，因此工业界对模拟电路的需求变得日益迫切，甚至要求模拟电路迅速赶上数字电路制造工艺进步的步伐，采用与数字电路同步先进的工艺技术，提供高性能、低功耗的模拟电路单元，即要求采用 CMOS 技术的模拟电路设计速度要追随摩尔定律的速度。

对于模拟电路设计者，采用先进的数字 CMOS 工艺设计高性能的电路是一项严峻的挑战。器件特性的非线性、噪声、先进数字工艺条件下电源电压的不断降低、特征尺寸变小后寄生参数对模拟特性的影响等，都是模拟电路设计者面临的挑战。Behzad Razavi 教授在美国加州大学洛杉矶分校（University of California at Los Angeles，UCLA）电机系从教多年，在无线收发器、宽带数据通信、锁相等电路方面造诣颇深，精通微电子学基础、射频微电子学、光通信接口电路、数据变换电路以及高速锁相环路等应用领域的电路设计技术，在这些领域成果彰显、著述颇丰。Razavi 教授所著的《模拟 CMOS 集成电路设计》的第一稿出版于 2000 年年初，当时 CMOS 技术进步迅速，迫切需要新的设计方法，本书的第一版满足了这种需求，出版后多次重印和修订再版，技术内容覆盖了 CMOS 模拟集成电路分析和设计的完整流程，包含了模拟电路设计师成功设计电路所需的最基础的知识。现在呈现在读者面前的是作者修

订后的版本，在新版中，Razavi 教授保持了其对电路本身深度洞察的优势，直观地告诉读者电路本身如何工作、电路如何偏置等基础问题，增加了将先进 CMOS 制造工艺引入模拟电路设计而产生的新问题，无论是在校学生还是模拟电路设计工程师，都可以从本书中学到 Razavi 教授关于电路理论的思维方法，并从中获益。

本书涉及的内容全面，涵盖了 MOS 晶体管结构与原理、基本放大电路单元、反馈与放大器性能的改善、稳定性等基本电路的分析与设计方法；包含了集成无源器件、电流基准源、镜像电流源、电压基准源、频率基准源等有源电路单元的设计技术；还提供了运算放大器、锁相环路、离散时间电路等集成模拟系统设计的基础知识。本书例题、习题的种类和数量较大，能够给学生提供充分的训练机会。

本书的第 16 章，简明扼要地讨论 MOS 晶体管短沟道效应，可提醒越来越多的采用先进 CMOS 工艺设计模拟电路的读者关注这个问题，具备了这些基础知识，读者可以通过自行阅读最新的文献，学习在纳米量级工艺下设计模拟电路的能力。第 17 章和第 18 章分别介绍 CMOS 制造工艺的基本知识和讨论版图设计及封装的基础知识。了解工艺特性，熟知版图设计和封装对电路性能的影响，才能成功设计出模拟集成电路。通常人们认为模拟电路设计是一种科学和技术，同时也是一种带有创造性的艺术；本书最后三章是需要在实践中逐渐体会的知识。

《模拟 CMOS 集成电路设计》是国内出版的最有影响力的美国电子科学与技术学科教材之一，出版过中译版和影印版。现在机械工业出版社购得其版权注释出版，使得该教材的最新进展得以及时反映，实为读者之幸事。采用本书作为教材，可以使读者掌握 CMOS 模拟集成电路的知识和设计方法，学习 CMOS 模拟集成电路的设计技巧，训练在复杂的模拟电路指标和规范间折中寻优的习惯，使学生逐渐成为一个成功的模拟电路设计师。

改革开放使得我们能够方便地阅读世界上优秀的教材。本书是众多国外电路教材中较为成熟的经典教材和参考书。

王志华

2013 年 6 月 16 日

About the Author

Behzad Razavi received the B.Sc. degree in electrical engineering from Sharif University of Technology in 1985 and the M.Sc. and Ph.D. degrees in electrical engineering from Stanford University in 1988 and 1992, respectively. He was with AT&T Bell Laboratories and subsequently Hewlett-Packard Laboratories until 1996. Since September 1996, he has been an Associate Professor and subsequently a Professor of electrical engineering at University of California, Los Angeles. His current research includes wireless transceivers, frequency synthesizers, phase-locking and clock recovery for high-speed data communications, and data converters.

Professor Razavi served as an Adjunct Professor at Princeton University, Princeton, NJ, from 1992 to 1994, and at Stanford University in 1995. He is a member of the Technical Program Committees of the Symposium on VLSI Circuits and the International Solid-State Circuits Conference (ISSCC), in which he is the chair of the Analog Subcommittee. He has also served as Guest Editor and Associate Editor of the IEEE Journal of Solid-State Circuits, IEEE Transactions on Circuits and Systems, and International Journal of High Speed Electronics.

Professor Razavi received the Beatrice Winner Award for Editorial Excellence at the 1994 ISSCC, the best paper award at the 1994 European Solid-State Circuits Conference, the best panel award at the 1995 and 1997 ISSCC, the TRW Innovative Teaching Award in 1997, and the best paper award at the IEEE Custom Integrated Circuits Conference in 1998. He is the author of *Principles of Data Conversion System Design* (IEEE Press, 1995), and *RF Microelectronics* (Prentice Hall, 1998), and the editor of *Monolithic Phase-Locked Loops and Clock Recovery Circuits* (IEEE Press, 1996).

Preface

In the past two decades, CMOS technology has rapidly embraced the field of analog integrated circuits, providing low-cost, high-performance solutions and rising to dominate the market. While silicon bipolar and III-V devices still find niche applications, only CMOS processes have emerged as a viable choice for the integration of today's complex mixed-signal systems. With channel lengths projected to scale down to 0.03 μm, CMOS technology will continue to serve circuit design for probably another two decades.

Analog circuit design itself has evolved with the technology as well. High-voltage, high-power analog circuits containing a few tens of transistors and processing small, continuous-time signals have gradually been replaced by low-voltage, low-power systems comprising thousands of devices and processing large, mostly discrete-time signals. For example, many analog techniques used only ten years ago have been abandoned because they do not lend themselves to low-voltage operation.

This book deals with the analysis and design of analog CMOS integrated circuits, emphasizing fundamentals as well as new paradigms that students and practicing engineers need to master in today's industry. Since analog design requires both intuition and rigor, each concept is first introduced from an intuitive perspective and subsequently treated by careful analysis. The objective is to develop both a solid foundation and methods of analyzing circuits by inspection so that the reader learns what approximations can be made in which circuits and how much error to expect in each approximation. This approach also enables the reader to apply the concepts to bipolar circuits with little additional effort.

I have taught most of the material in this book both at UCLA and in industry, polishing the order, the format, and the content with every offering. As the reader will see throughout the book, I follow four "golden rules" in writing (and teaching): (1) I explain *why* the reader needs to know the concept that is to be studied; (2) I put myself in the reader's position and predict the questions that he/she may have while reading the material for the first time; (3) With Rule 2 in mind, I pretend to know only as much as the (first-time) reader and try to "grow" with him/her, thereby experiencing the same thought process; (4) I begin with the "core" concept in a simple (even imprecise) language and gradually add necessary modifications to arrive at the final (precise) idea. The last rule is particularly important in teaching circuits because it allows the reader to observe the evolution of a topology and hence learn both analysis and synthesis.

The text comprises 18 chapters whose contents and order are carefully chosen to provide a natural flow for both self-study and classroom adoption in quarter or semester systems.

Unlike some other books on analog design, we cover only a *bare minimum* of MOS device physics at the beginning, leaving more advanced properties and fabrication details for later chapters. To an expert, the elementary device physics treatment may appear oversimplified, but my experience suggests that (a) first-time readers simply do not absorb the high-order device effects and fabrication technology before they study circuits because they do not see the relevance; (b) if properly presented, even the simple treatment proves adequate for a substantial coverage of basic circuits; (c) readers learn advanced device phenomena and processing steps much more readily *after* they have been exposed to a significant amount of circuit analysis and design.

Chapter 1 provides the reader with motivation for learning the material in this book.

Chapter 2 describes basic physics and operation of MOS devices.

Chapters 3 through 5 deal with single-stage and differential amplifiers and current mirrors, respectively, developing efficient analytical tools for quantifying the behavior of basic circuits by inspection.

Chapters 6 and 7 introduce two imperfections of circuits, namely, frequency response and noise. Noise is treated at an early stage so that it "sinks in" as the reader accounts for its effects in subsequent circuit developments.

Chapters 8 through 10 describe feedback, operational amplifiers, and stability in feedback systems, respectively. With the useful properties of feedback analyzed, the reader is motivated to design high-performance, stable op amps and understand the trade-offs between speed, precision, and power dissipation.

Chapters 11 through 13 deal with more advanced topics: bandgap references, elementary switched-capacitor circuits, and the effect of nonlinearity and mismatch. These three subjects are included here because they prove essential in most analog and mixed-signal systems today.

Chapters 14 and 15 concentrate on the design of oscillators and phase-locked loops, respectively. In view of the wide usage of these circuits, a detailed study of their behavior and many examples of their operation are provided.

Chapter 16 is concerned with high-order MOS device effects and models, emphasizing the circuit design implications. If preferred, this chapter can directly follow Chapter 2 as well. Chapter 17 describes CMOS fabrication technology with a brief overview of layout design rules.

Chapter 18 presents the layout and packaging of analog and mixed-signal circuits. Many practical issues that directly impact the performance of the circuit are described and various techniques are introduced.

The reader is assumed to have a basic knowledge of electronic circuits and devices, e.g., *pn* junctions, the concept of small-signal operation, equivalent circuits, and simple biasing. For a senior-level elective course, Chapters 1 through 8 can be covered in a quarter and Chapters 1 through 10 in a semester. For a first-year graduate course, Chapters 1 through 11 plus one of Chapters 12 through 15 can be taught in one quarter, and the first 16 chapters in one semester.

The problem sets at the end of each chapter are designed to extend the reader's understanding of the material and complement it with additional practical considerations. A solutions manual is available for instructors.

Behzad Razavi
July 2000

Acknowledgments

Writing a book begins with a great deal of excitement. However, after two years of relentless writing, drawing, and revising, when the book exceeds 600 pages and it is almost impossible to make the equations and subscripts and superscripts in the last chapter consistent with those in the first, the author begins to feel the streaks of insanity, realizing that the book will never finish without the support of many other people.

This book has benefited from the contributions of many individuals. A number of UCLA students read the first draft and the preview edition sentence by sentence. In particular, Alireza Zolfaghari, Ellie Cijvat, and Hamid Rafati meticulously read the book and found several hundred errors (some quite subtle). Also, Emad Hegazi, Dawei Guo, Alireza Razzaghi, Jafar Savoj, and Jing Tian made helpful suggestions regarding many chapters. I thank all.

Many experts in academia and industry read various parts of the book and provided useful feedback. Among them are Brian Brandt (National Semiconductor), Matt Corey (National Semiconductor), Terri Fiez (Oregon State University), Ian Galton (UC San Diego), Ali Hajimiri (Caltech), Stacy Ho (Analog Devices), Yin Hu (Texas Instruments), Shen-Iuan Liu (National Taiwan University), Joe Lutsky (National Semiconductor), Amit Mehrotra (University of Illinois, Urbana-Champaign), David Robertson (Analog Devices), David Su (T-Span), Tao Sun (National Semiconductor), Robert Taft (National Semiconductor), and Masoud Zargari (T-Span). Jason Woo (UCLA) patiently endured and answered my questions about device physics. I thank all.

Ramesh Harjani (University of Minnesota), John Nyenhius (Purdue University), Norman Tien (Cornell University), and Mahmoud Wagdy (California State University, Long Beach) reviewed the book proposal and made valuable suggestions. I thank all.

My wife, Angelina, has made many contributions to this book, from typing chapters to finding numerous errors and raising questions that made me reexamine my own understanding. I am very grateful to her.

The timely production of the book was made possible by the hard work of the staff at McGraw-Hill, particularly, Catherine Fields, Michelle Flomenhoft, Heather Burbridge, Denise Santor-Mitzit, and Jim Labeots. I thank all.

I learned analog design from two masters: Mehrdad Sharif-Bakhtiar (Sharif University of Technology) and Bruce Wooley (Stanford University) and it is only appropriate that I express my gratitude to them here. What I inherited from them will be inherited by many generations of students.

Behzad Razavi
July 2000

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