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Behzad Razavi

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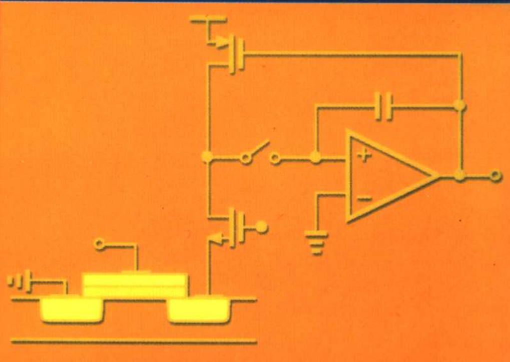
Design of Analog CMOS Integrated Circuits



Behzad Razavi

McGRAW-HILL INTERNATIONAL EDITION
Electrical Engineering Series

清华大学出版社

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EISBN: 0-07-238032-2

北京市版权局著作权合同登记号 图字: 01-2005-2105

图书在版编目(CIP)数据

模拟 CMOS 集成电路设计 = Design of Analog CMOS Integrated Circuits/(美)罗扎(Razavi, B.)著. —影印本. —北京: 清华大学出版社, 2005. 8
(国外大学优秀教材——微电子类系列)
ISBN 7-302-10886-2

Ⅰ. 模… Ⅱ. 罗… Ⅲ. 模拟集成电路—电路设计—高等学校—教材—英文 Ⅳ. TN431. 102

中国版本图书馆 CIP 数据核字(2005)第 037981 号

出 版 者: 清华大学出版社
http://www. tup. com. cn
社总机: 010-62770175
地 址: 北京清华大学学研大厦
邮 编: 100084
客户服务: 010-62776969
责任编辑: 田志明
印 刷 者: 北京市世界知识印刷厂
装 订 者: 三河市春园印刷有限公司
发 行 者: 新华书店总店北京发行所
开 本: 185 × 230 **印张**: 44. 25
版 次: 2005 年 8 月第 1 版 2005 年 8 月第 1 次印刷
书 号: ISBN 7-302-10886-2/TN · 248
印 数: 1 ~ 3000
定 价: 68. 00 元

出版前言

微电子技术是信息科学技术的核心技术之一，微电子产业是是当代高新技术产业群的核心和维护国家主权、保障国家安全的战略性产业。我国在《信息产业“十五”计划纲要》中明确提出：坚持自主发展，增强创新能力和核心竞争力，掌握以集成电路和软件技术为重点的信息产业的核心技术，提高具有自主知识产权产品的比重。发展集成电路技术的关键之一是培养具有国际竞争力的专业人才。

微电子技术发展迅速，内容更新快，而我国微电子专业图书数量少，且内容和体系不能反映科技发展的水平，不能满足培养人才的需求，为此，我们系统挑选了一批国外经典教材和前沿著作，组织分批出版。图书选择的几个基本原则是：在本领域内广泛采用，有很大影响力；内容反映科技的最新发展，所述内容是本领域的研究热点；编写和体系与国内现有图书差别较大，能对我国微电子教育改革有所启示。本套丛书还侧重于微电子技术的实用性，选取了一批集成电路设计方面的工程技术用书，使读者能方便地应用于实践。本套丛书不仅能作为相关课程的教科书和教学参考书，也可作为工程技术人员的自学读物。

我们真诚地希望，这套丛书能给国内高校师生、工程技术人员以及科研人员的学习和工作有所帮助，对推动我国集成电路的发展有所促进。也衷心期望着广大读者对我们一如既往的关怀和支持，鼓励我们出版更多、更好的图书。

清华大学出版社

Design of Analog CMOS Integrated Circuits

影 印 版 序

模拟集成电路设计一直在集成电路的设计中占据着极其重要的位置。由于宏观信号从本质上来讲都是模拟信号，因此从现实世界获取信号、进行放大和处理并最终返回现实世界实现驱动都离不开模拟集成电路。模拟集成电路不仅在许多领域起着数字电路所不能取代的作用，而且在许多具体实现中还胜过数字电路。近年来，随着 MOS 器件尺寸的持续缩小和 CMOS 集成电路的飞速发展，当代集成电路的设计和生产已经达到了特大规模（ULSI）乃至吉规模（GSI）的水平，片上系统（SoC）不仅成为人们追求的目标，而且正在成为现实。可以毫不夸张地说，没有 CMOS 技术的发展就没有现代数字集成电路的辉煌，同样可以毫不夸张地说，没有 CMOS 模拟集成电路的发展，就没有需要同时将大规模数字和模拟电路集成在一起进行混合信号处理的片上系统。

模拟集成电路的设计与其说是一门技术，还不如说是一门艺术，或者说是技术和艺术的融合。它比数字集成电路设计需要更严格的分析和更丰富的直觉。严谨坚实的理论无疑是严格分析能力的基石，而设计者的实践经验无疑是诞生丰富直觉的源泉。这也正是初学者对学习模拟集成电路设计感到困惑并难以驾驭的根本原因。所幸的是，美国加州大学洛杉机分校（UCLA）教授 Behzad Razavi 凭借着他在美国多所著名大学执教多年的丰富教学经验和在世界知名顶级公司(如 AT&T、Bell Lab 以及 HP)卓著的研究经历为我们提供了一本优秀的教材，即 McGraw-Hill 出版的《模拟 CMOS 集成电路设计》（Design of Analog CMOS Integrated Circuits）。这本书自 2000 年出版以来得到了国内外读者的好评和青睐，被许多国际知名大学选为大学教科书。现在清华大学出版社在保留原书全部内容的基础上作一些结构上的调整以影印方式出版，以满足国内广大读者学习和参考的需要。

全书共分十五章，第一章介绍了模拟电路设计的基本概念，说明了 CMOS 模拟集成电路设计技术的重要作用。第二章描述了 MOS 器件的物理模型及工作特性，这是全书内容的器件物理基础。第三章至第五章分别介绍了单级放大器、差分放大器和电流镜电路，它们是 CMOS 模拟集成电路的基本电路。学习这些内容可以初步培养起通过观察电路拓扑结构高效率地直觉分析模拟电路的能力。第六章和第七章说明了限制模拟电路工作性能的两个重要因素：频率特性和噪声。它们对后续各章的分析有着重要的意义。第八章至第十章

介绍了反馈、运算放大器以及反馈系统的稳定性问题，从中读者可以学习如何运用反馈的有益特性来设计高性能和稳定的运算放大器，帮助读者理解各项设计指标如速度、精度和功耗之间的相互影响及在设计过程中的综合考虑和平衡。本书的其余各章介绍较深的内容：第十一章介绍能隙基准电源，第十二章介绍开关电容电路，第十三章介绍非线性和失匹配问题，第十四章介绍振荡器，第十五章介绍锁相环。其中非线性和失匹配问题在所有的模拟电路和混合信号电路中几乎都会遇到，而能隙基准电源、开关电容电路、振荡器以及锁相环的应用领域非常广泛，因此可以把这些内容看成是前十章理论和基础知识的深化和延伸，也可以看成是紧密联系实际的具体应用和设计实践。考虑到原书第十六章至第十八章有关短沟道 MOS 器件的高阶效应和模型、CMOS 工艺以及版图和封装技术的内容可能在其他课程涉及并且大部分集成电路的参考书中都已列入，因此在出版本书时将这几部分的内容归入改编为附录，这样既使教师在组织课程教学时可灵活选用，又使需要这部分内容的读者能即时参考。

本书可作为国内大学电子类和自动化类专业本科生和研究生模拟集成电路课程的教科书。教学内容可以根据实际情况选取本书相应的章节进行组合。例如，作为本科生教材时，可覆盖第一章至第十章，并可选取后续章节的部分内容（例如第十一章能隙基准电源和第十四章振荡器）作为知识的拓展和设计应用举例。作为研究生教材时，可以在简要复习前八章的基础上直接从第九章运算放大器开始覆盖到第十五章。无论是本科生课程还是研究生课程，本书的第二章（MOS 器件物理）和附录的内容都可以由教师根据课程的深浅程度和学生的背景基础合理选用，或作为学生自学的材料。书中各章都有大量的分析或设计实例以加深读者理解，各章后附有习题，并为教师提供习题答案。由于原著者 Behzad Razavi 教授在世界知名顶级公司的丰富研究经历，使本书的内容不仅适合于教学，而且也非常适合作为 CMOS 模拟集成电路设计或相关领域的研究人员和工程技术人员的参考书。值得一提的是，本书作者的另一本书《射频微电子》（RF Microelectronics）影印版已由清华大学出版社出版，中译本也将由该出版社出版，对于希望在 CMOS 射频集成电路方面有所建树而又需要补充 CMOS 模拟集成电路设计基础知识的读者，不失为极佳的选择。

周润德

2004 年 11 月于清华园

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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