国外电子与通信教材系列

英文版

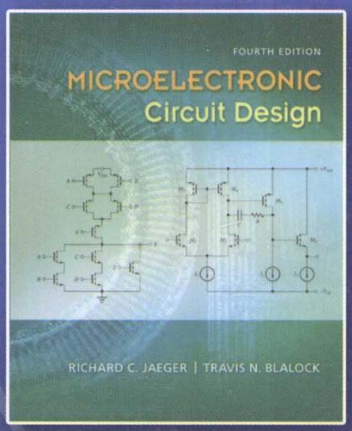
Mc Graw Hill Education

微电子电路设计

（第四版）

Microelectronic Circuit Design

Fourth Edition



[美] Richard C. Jaeger
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北京 · BEIJING

内容简介

本书涵盖了微电子电路设计所需基础知识，主要由三个部分组成。第一部分介绍固态电子学与器件，讨论了电子学的发展与电路分析方法、半导体物理和以MOSFET和双极型晶体管为代表的微电子器件的工作原理、$i-v$特性及SPICE模型等。第二部分为数字电路，包括数字电路的基本概念和CMOS电路、存储电路、ECL与TTL等双极型逻辑电路的设计方法，并简要介绍了BiCMOS电路。第三部分为模拟电路，以理想运算放大器和SPICE仿真为基础介绍了不同结构运算放大器的相关特性、小信号模型、具体分析方法和集成设计技术，最后讨论了放大器的频率响应、反馈和振荡器等问题。通过学习本书可以全面了解现代微电子电路设计，包括模拟与数字、分立与集成，了解内部结构也有利于系统设计中对集成电路的适当选择。

本书适用做电子信息类各专业本科生基础课的双语教材或参考书，也可作为研究生或相关领域工程技术人员的参考资料。

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序

2001年7月间，电子工业出版社的领导同志邀请各高校十几位通信领域方面的老师，商量引进国外教材问题。与会同志对出版社提出的计划十分赞同，大家认为，这对我国通信事业、特别是对高等院校通信学科的教学工作会很有好处。

教材建设是高校教学建设的主要内容之一。编写、出版一本好的教材，意味着开设了一门好的课程，甚至可能预示着一个崭新学科的诞生。20世纪40年代MIT林肯实验室出版的一套28本雷达丛书，对近代电子学科、特别是对雷达技术的推动作用，就是一个很好的例子。

我国领导部门对教材建设一直非常重视。20世纪80年代，在原教委教材编审委员会的领导下，汇集了高等院校几百位富有教学经验的专家，编写、出版了一大批教材；很多院校还根据学校的特点和需要，陆续编写了大量的讲义和参考书。这些教材对高校的教学工作发挥了极好的作用。近年来，随着教学改革不断深入和科学技术的飞速进步，有的教材内容已比较陈旧、落后，难以适应教学的要求，特别是在电子学和通信技术发展神速、可以讲是日新月异的今天，如何适应这种情况，更是一个必须认真考虑的问题。解决这个问题，除了依靠高校的老师和专家撰写新的符合要求的教科书外，引进和出版一些国外优秀电子与通信教材，尤其是有选择地引进一批英文原版教材，是会有好处的。

一年多来，电子工业出版社为此做了很多工作。他们成立了一个“国外电子与通信教材系列”项目组，选派了富有经验的业务骨干负责有关工作，收集了230余种通信教材和参考书的详细资料，调来了100余种原版教材样书，依靠由20余位专家组成的出版委员会，从中精选了40多种，内容丰富，覆盖了电路理论与应用、信号与系统、数字信号处理、微电子、通信系统、电磁场与微波等方面，既可作为通信专业本科生和研究生的教学用书，也可作为有关专业人员的参考材料。此外，这批教材，有的翻译为中文，还有部分教材直接影印出版，以供教师用英语直接授课。希望这些教材的引进和出版对高校通信教学和教材改革能起一定作用。

在这里，我还要感谢参加工作的各位教授、专家、老师与参加翻译、编辑和出版的同志们。各位专家认真负责、严谨细致、不辞辛劳、不怕琐碎和精益求精的态度，充分体现了中国教育工作者和出版工作者的良好美德。

随着我国经济建设的发展和科学技术的不断进步，对高校教学工作会不断提出新的要求和希望。我想，无论如何，要做好引进国外教材的工作，一定要联系我国的实际。教材和学术专著不同，既要注意科学性、学术性，也要重视可读性，要深入浅出，便于读者自学；引进的教材要适应高校教学改革的需要，针对目前一些教材内容较为陈旧的问题，有目的地引进一些先进的和正在发展中的交叉学科的参考书；要与国内出版的教材相配套，安排好出版英文原版教材和翻译教材的比例。我们努力使这套教材能尽量满足上述要求，希望它们能放在学生们的课桌上，发挥一定的作用。

最后，预祝“国外电子与通信教材系列”项目取得成功，为我国电子与通信教学和通信产业的发展培土施肥。也恳切希望读者能对这些书籍的不足之处、特别是翻译中存在的问题，提出意见和建议，以便再版时更正。

吴佑寿

中国工程院院士、清华大学教授

“国外电子与通信教材系列”出版委员会主任

出 版 说 明

进入21世纪以来，我国信息产业在生产和科研方面都大大加快了发展速度，并已成为国民经济发展的支柱产业之一。但是，与世界上其他信息产业发达的国家相比，我国在技术开发、教育培训等方面都还存在着较大的差距。特别是在加入WTO后的今天，我国信息产业面临着国外竞争对手的严峻挑战。

作为我国信息产业的专业科技出版社，我们始终关注着全球电子信息技术的发展方向，始终把引进国外优秀电子与通信信息技术教材和专业书籍放在我们工作的重要位置上。在2000年至2001年间，我社先后从世界著名出版公司引进出版了40余种教材，形成了一套“国外计算机科学教材系列”，在全国高校以及科研部门中受到了欢迎和好评，得到了计算机领域的广大教师与科研工作者的充分肯定。

引进和出版一些国外优秀电子与通信教材，尤其是有选择地引进一批英文原版教材，将有助于我国信息产业培养具有国际竞争能力的技术人才，也将有助于我国国内在电子与通信教学工作中掌握和跟踪国际发展水平。根据国内信息产业的现状、教育部《关于“十五”期间普通高等教育教材建设与改革的意见》的指示精神以及高等院校老师们反映的各种意见，我们决定引进“国外电子与通信教材系列”，并随后开展了大量准备工作。此次引进的国外电子与通信教材均来自国际著名出版商，其中影印教材约占一半。教材内容涉及的学科方向包括电路理论与应用、信号与系统、数字信号处理、微电子、通信系统、电磁场与微波等，其中既有本科专业课程教材，也有研究生课程教材，以适应不同院系、不同专业、不同层次的师生对教材的需求，广大师生可自由选择和自由组合使用。我们还将与国外出版商一起，陆续推出一些教材的教学支持资料，为授课教师提供帮助。

此外，“国外电子与通信教材系列”的引进和出版工作得到了教育部高等教育司的大力支持和帮助，其中的部分引进教材已通过“教育部高等学校电子信息科学与工程类专业教学指导委员会”的审核，并得到教育部高等教育司的批准，纳入了“教育部高等教育司推荐——国外优秀信息科学与技术系列教学用书”。

为做好该系列教材的翻译工作，我们聘请了清华大学、北京大学、北京邮电大学、南京邮电大学、东南大学、西安交通大学、天津大学、西安电子科技大学、电子科技大学、中山大学、哈尔滨工业大学、西南交通大学等著名高校的教授和骨干教师参与教材的翻译和审校工作。许多教授在国内电子与通信专业领域享有较高的声望，具有丰富的教学经验，他们的渊博学识从根本上保证了教材的翻译质量和专业学术方面的严格与准确。我们在此对他们的辛勤工作与贡献表示衷心的感谢。此外，对于编辑的选择，我们达到了专业对口；对于从英文原书中发现的错误，我们通过与作者联络、从网上下载勘误表等方式，逐一进行了修订；同时，我们对审校、排版、印制质量进行了严格把关。

今后，我们将进一步加强同各高校教师的密切关系，努力引进更多的国外优秀教材和教学参考书，为我国电子与通信教材达到世界先进水平而努力。由于我们对国内外电子与通信教育的发展仍存在一些认识上的不足，在选题、翻译、出版等方面的工作中还有许多需要改进的地方，恳请广大师生和读者提出批评及建议。

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PREFACE

Through study of this text, the reader will develop a comprehensive understanding of the basic techniques of modern electronic circuit design, analog and digital, discrete and integrated. Even though most readers may not ultimately be engaged in the design of integrated circuits (ICs) themselves, a thorough understanding of the internal circuit structure of ICs is prerequisite to avoiding many pitfalls that prevent the effective and reliable application of integrated circuits in system design.

Digital electronics has evolved to be an extremely important area of circuit design, but it is included almost as an afterthought in many introductory electronics texts. We present a more balanced coverage of analog and digital circuits. The writing integrates the authors' extensive industrial backgrounds in precision analog and digital design with their many years of experience in the classroom. A broad spectrum of topics is included, and material can easily be selected to satisfy either a two-semester or three-quarter sequence in electronics.

IN THIS EDITION

This edition continues to update the material to achieve improved readability and accessibility to the student. In addition to general material updates, a number of specific changes have been included in Parts I and II, Solid-State Electronics and Devices and Digital Electronics, respectively. A new closed-form solution to four-resistor MOSFET biasing is introduced as well as an improved iterative strategy for diode Q-point analysis. JFET devices are important in analog design and have been reintroduced at the end of Chapter 4. Simulation-based logic gate scaling is introduced in the MOS logic chapters, and an enhanced discussion of noise margin is included as a new Electronics-in-Action (EIA) feature. Current-mode logic (CML) is heavily used in high performance SiGe ICs, and a CML section is added to the Bipolar Logic chapter.

This revision contains major reorganization and revision of the analog portion (Part III) of the text. The introductory amplifier material (old Chapter 10) is now introduced in a "just-in-time" basis in the three op-amp chapters. Specific sections have been added with qualitative descriptions of the operation of basic op-amp circuits and each transistor amplifier configuration as well as the transistors themselves.

Feedback analysis using two-ports has been eliminated from Chapter 18 in favor of a consistent loop-gain analysis approach to all feedback configurations that begins in the op-amp chapters. The important successive voltage and current injection technique for finding loop-gain is now included in Chapter 11, and Blackman's theorem is utilized to find input and output resistances of closed-loop amplifiers. SPICE examples have been modified to utilize three- and five-terminal built-in op-amp models.

Chapter 10, Analog Systems and Ideal Operational Amplifiers, provides an introduction to amplifiers and covers the basic ideal op-amp circuits.

Chapter 11, Characteristics and Limitations of Operational Amplifiers, covers the limitations of nonideal op amps including frequency response and stability and the four classic feedback circuits including series-shunt, shunt-shunt, shunt-series and series-series feedback amplifiers.

Chapter 12, Operational Amplifier Applications, collects together all the op-amp applications including multistage amplifiers, filters, A/D and D/A converters, sinusoidal oscillators, and multivibrators.

Redundant material in transistor amplifier chapters 13 and 14 has been merged or eliminated wherever possible. Other additions to the analog material include discussion of relations between MOS logic inverters and common-source amplifiers, distortion reduction through feedback, the relationship between step response and phase margin, NMOS differential amplifiers with NMOS load transistors, the regulated cascode current source, and the Gilbert multiplier.

Because of the renaissance and pervasive use of RF circuits, the introductory section on RF amplifiers, now in Chapter 17, has been expanded to include shunt-peaked and tuned amplifiers, and the use of inductive degeneration in common-source amplifiers. New material on mixers includes passive, active, single- and double-balanced mixers and the widely used Gilbert mixer.

Chapter 18, Transistor Feedback Amplifiers and Oscillators, presents examples of transistor feedback amplifiers and transistor oscillator implementations. The transistor oscillator section has been expanded to include a discussion of negative resistance in oscillators and the negative G_m oscillator cell.

Several other important enhancements include:

- SPICE support on the web now includes examples in NI Multisim™ software in addition to PSpice®.
- At least 35 percent revised or new problems.
- New PowerPoint® slides are available from McGraw-Hill.
- A group of tested design problems are also available.

The Structured Problem Solving Approach continues to be utilized throughout the examples. We continue to expand the popular Electronics-in-Action Features with the addition of Diode Rectifier as an AM Demodulator; High Performance CMOS Technologies; A Second Look at Noise Margins (graphical flip-flop approach); Offset Voltage, Bias Current and CMRR Measurement; Sample-and-Hold Circuits; Voltage Regulator with Series Pass Transistor; Noise Factor, Noise Figure and Minimum Detectable Signal; Series-Parallel and Parallel-Series Network Transformations; and Passive Diode Ring Mixer.

Chapter Openers enhance the readers understanding of historical developments in electronics. Design notes highlight important ideas that the circuit designer should remember. The World Wide Web is viewed as an integral extension of the text, and a wide range of supporting materials and resource links are maintained and updated on the McGraw-Hill website (www.mhhe.com/jaeger).

Features of the book are outlined below.

The Structured Problem-Solving Approach is used throughout the examples.

Electronics-in-Action features in each chapter.

Chapter openers highlighting developments in the field of electronics.

Design Notes and emphasis on practical circuit design.

Broad use of SPICE throughout the text and examples.

Integrated treatment of device modeling in SPICE.

Numerous Exercises, Examples, and Design Examples.

Large number of new problems.

Integrated web materials.

Continuously updated web resources and links.

Placing the digital portion of the book first is also beneficial to students outside of electrical engineering, particularly computer engineering or computer science majors, who may only take the first course in a sequence of electronics courses.

The material in Part II deals primarily with the internal design of logic gates and storage elements. A comprehensive discussion of NMOS and CMOS logic design is presented in Chapters 6 and 7, and a discussion of memory cells and peripheral circuits appears in Chapter 8. Chapter 9 on bipolar logic design includes discussion of ECL, CML and TTL. However, the material on bipolar logic has been reduced in deference to the import of MOS technology. This text does not include any substantial design at the logic block level, a topic that is fully covered in digital design courses.

Parts I and II of the text deal only with the large-signal characteristics of the transistors. This allows readers to become comfortable with device behavior and i-v characteristics before they have to grasp the concept of splitting circuits into different pieces (and possibly different topologies) to perform dc and ac small-signal analyses. (The concept of a small-signal is formally introduced in Part III, Chapter 13.)

Although the treatment of digital circuits is more extensive than most texts, more than 50 percent of the material in the book, Part III, still deals with traditional analog circuits. The analog section begins in Chapter 10 with a discussion of amplifier concepts and classic ideal op-amp circuits. Chapter 11 presents a detailed discussion of nonideal op amps, and Chapter 12 presents a range of op-amp applications. Chapter 13 presents a comprehensive development of the small-signal models for the diode, BJT, and FET. The hybrid-pi model and pi-models for the BJT and FET are used throughout.

Chapter 14 provides in-depth discussion of single-stage amplifier design and multistage ac coupled amplifiers. Coupling and bypass capacitor design is also covered in Chapter 14. Chapter 15 discusses dc coupled multistage amplifiers and introduces prototypical op amp circuits. Chapter 16 continues with techniques that are important in IC design and studies the classic 741 operational amplifier.

Chapter 17 develops the high-frequency models for the transistors and presents a detailed discussion of analysis of high-frequency circuit behavior. The final chapter presents examples of transistor feedback amplifiers. Discussion of feedback amplifier stability and oscillators conclude the text.

DESIGN

Design remains a difficult issue in educating engineers. The use of the well-defined problem-solving methodology presented in this text can significantly enhance the students ability to understand issues related to design. The design examples assist in building an understanding of the design process.

Part II launches directly into the issues associated with the design of NMOS and CMOS logic gates. The effects of device and passive-element tolerances are discussed throughout the text. In today's world, low-power, low-voltage design, often supplied from batteries, is playing an increasingly important role. Logic design examples have moved away from 5 V to lower power supply levels. The use of the computer, including MATLAB®, spreadsheets, or standard high-level languages to explore design options is a thread that continues throughout the text.

Methods for making design estimates and decisions are stressed throughout the analog portion of the text. Expressions for amplifier behavior are simplified beyond the standard hybrid-pi model expressions whenever appropriate. For example, the expression for the voltage gain of an amplifier in most texts is simply written as $|A_v| = g_m R_L$, which tends to hide the power supply voltage as the fundamental design variable. Rewriting this expression in approximate form as $g_m R_L \cong 10V_{CC}$ for the BJT, or $g_m R_L \cong V_{DD}$ for the FET, explicitly displays the dependence of amplifier design on the choice of power supply voltage and provides a simple first-order design estimate for the voltage gain of the common-emitter and common-source amplifiers. The gain advantage of the BJT stage is also clear. These approximation techniques and methods for performance estimation are included as often as possible. Comparisons and design tradeoffs between the properties of BJTs and FETs are included throughout Part III.

Worst-case and Monte-Carlo analysis techniques are introduced at the end of the first chapter. These are not topics traditionally included in undergraduate courses. However, the ability to design circuits in the face of wide component tolerances and variations is a key component of electronic circuit design, and the design of circuits using standard components and tolerance assignment are discussed in examples and included in many problems.

PROBLEMS AND INSTRUCTOR SUPPORT

Specific design problems, computer problems, and SPICE problems are included at the end of each chapter. Design problems are indicated by ○, computer problems are indicated by 💻, and SPICE problems are indicated by S. The problems are keyed to the topics in the text with the more difficult or time-consuming problems indicated by * and **. An Instructor's Manual containing solutions to all the problems is available from the authors. In addition, the graphs and figures are available as PowerPoint files and can be retrieved from the website. Instructor notes are available as PowerPoint slides.

ELECTRONIC TEXTBOOK OPTION

This text is offered through CourseSmart for both instructors and students. CourseSmart is an online resource where students can purchase the complete text online at almost half the cost of a traditional text. Purchasing the eTextbook allows students to take advantage of CourseSmart's web tools for learning, which include full text search, notes and highlighting, and email tools for sharing notes between classmates. To learn more about CourseSmart options, contact your sales representative or visit www.CourseSmart.com.

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COMPUTER USAGE AND SPICE

The computer is used as a tool throughout the text. The authors firmly believe that this means more than just the use of the SPICE circuit analysis program. In today's computing environment, it is often appropriate to use the computer to explore a complex design space rather than to try to reduce a complicated set of equations to some manageable analytic form. Examples of the process of setting up equations for iterative evaluation by computer through the use of spreadsheets, MATLAB, and/or standard high-level language programs are illustrated in several places in the text. MATLAB is also used for Nyquist and Bode plot generation and is very useful for Monte Carlo analysis.

On the other hand, SPICE is used throughout the text. Results from SPICE simulation are included throughout and numerous SPICE problems are to be found in the problem sets. Wherever helpful, a SPICE analysis is used with most examples. This edition also emphasizes the differences and utility of the dc, ac, transient, and transfer function analysis modes in SPICE. A discussion of SPICE

device modeling is included following the introduction to each semiconductor device, and typical SPICE model parameters are presented with the models.

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In developing this text, we have attempted to integrate our industrial backgrounds in precision analog and digital design with many years of experience in the classroom. We hope we have at least succeeded to some extent. Constructive suggestions and comments will be appreciated.

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