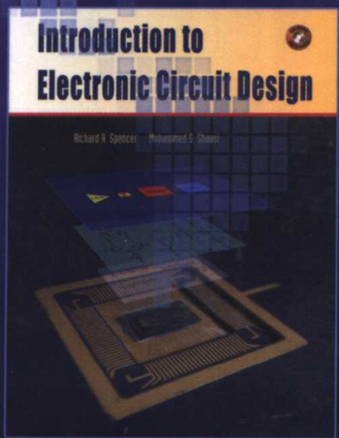
国外电子与通信教材系列

英文版

电子电路设计基础

Introduction to Electronic Circuit Design



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北京 · BEIJING

内 容 简 介

本书按照逻辑（而不是按照顺序）对内容进行组织，使读者在某个设计过程中能够对不同类型的分析进行比较。本书的特点如下：利用一个普通的晶体管介绍多种适用于FET和BJT电路的基本原理；将复杂问题进行分解；提供全面的针对练习的解决方案；等等。本书的主要内容有：电子电路设计，半导体物理与电子器件，固态器件制造，计算机辅助设计的工具与技巧，运算放大器，小信号线性与放大，直流偏置，低频小信号交流分析与放大器，放大器频率响应，反馈，滤波器与调制放大器，低频大信号交流分析，数据转换器，门级数字电路，晶体管级数字电路。本书适合作为高等院校电子类的本科生教材，也可作为该领域技术人员的参考书。

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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、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。

电子工业出版社

教材出版委员会

Preface

In the forward to the first issue of the *IEEE Journal of Solid-State Circuits* in September 1966, Dr. James D. Meindl wrote

> *"Within the past two decades, perhaps no sector of electronics has developed more rapidly than solid-state circuits. The nature of this development has imposed an expanding set of requirements on the breadth of knowledge one must possess in order to design a circuit well. – Most recently, the uniquely interdependent material, device, circuit, and system design considerations of large scale integration have again extended the scope of the problem of circuit design."*

It is remarkable that such broad statements, written over 30 years ago, are still accurate today. Given the complexity of present-day integrated circuits, circuit designers need to have a greater breadth of knowledge than ever before. This text is intended to provide an introduction to this important and rapidly changing discipline.

Many engineers who will never design an electronic circuit need to have a basic understanding of the characteristics of electronic circuits because they fabricate, test, or use these circuits, or they design systems that eventually have to be implemented using these circuits. In addition, there are many techniques and principles used in the design of electronic circuits that find widespread use outside of this discipline (e.g., small-signal linearity and feedback). Therefore, for those of you who will not become circuit designers this text still has much to offer that will be important in your careers.

The field of electrical engineering changes very rapidly. What can you expect to learn from this book that will still be useful in ten or twenty years? A great deal I hope. Although the devices, the economics of which components you favor, (e.g., resistors used to be cheaper than transistors, but the opposite is true in integrated circuits), and the computer-aided design tools will definitely change, there is still much that will stay the same. I can't predict exactly what will remain useful, but it seems unlikely that the *concept* of how to analyze a circuit so that you can see how to improve it will change, or that the *concept* of small-signal linearity will become unimportant, and certainly the ability you develop to solve problems will always be useful; after all, that is what engineers do.

I have tried to concentrate on helping you learn the *concepts* in this book. To be good at circuit design and many other engineering disciplines requires a healthy dose of intuition. While you certainly need to know how to write nodal equations and solve them, no one is going to pay you to do that because you can't possibly compete with a computer program. As soon as any area of engineering is well enough understood that we can write rigid procedures guaranteed to produce a correct answer, a computer program will take over. Therefore, it is true that you will always be working with systems that you don't completely understand and systems that cannot be analyzed exactly. Design will always require an ability to model the real system with a model that is simultaneously simple enough to allow you to "see" what is going on and think of ways to improve the performance, while being complete enough to adequately model the salient characteristics of the system. In addition, design requires that we do our analyses in a different way; we aren't just seeking the *answer*, but an understanding of how we can *modify* the system and/or *choose* the component values to achieve a desired result. That is, at least in part, what it takes to do design.

Therefore, I have focused on providing explanations and examples of how different circuits work and have focused on the underlying principles more than "rules of thumb" or design procedures, although some of these are certainly given. If you are searching for a cookbook approach, you won't find it here. However, remember that no one will pay you to follow set procedures. A designer is only valuable if he or she understands the problem well enough to come up with a good solution, even when no "procedure" exists.

This textbook came together when the second author, who was looking for someone to revise an existing text, met with the first author, who was contemplating writing a new book. After discussion, it was agreed that a new textbook was needed, but that material from the older text could be used. The result is the book you have in your hands; most of the material is completely new and written by the first author, but some of it is adapted from *Electronic Devices and Circuits: Discrete and Integrated*, by Mohammed S. Ghausi.

Organization and Features of the Text

The material in this text is organized logically by topic, rather than sequentially in the order I would present it. Therefore, I *do not expect* that you will read this book linearly. Rather, I expect that you will at times, jump around a bit. Organizing the book in this way has two advantages; first, I do not dictate the order of presentation and second, it emphasizes the different types of analyses that must be used in the design process.

Not specifying the order of presentation is important, because it allows each instructor more flexibility in choosing the topics to be covered and the depth of coverage of each topic. For example, you may cover field-effect transistor (FET) circuits first, or bipolar junction transistor (BJT) circuits first. This flexibility is partly brought about by placing the material on small-signal linearity in a separate chapter, and partly through the use of a generic transistor to present certain information that is common to both FETs and BJTs.

Emphasizing the different types of analyses used in design is important, because students are frequently confused about when and why a particular analysis or model should be used. For example, why is a capacitor modeled as an open or short circuit for some analyses while it is retained for others? And how do I know which model I should use for the transistors in my circuit? By covering DC bias point analysis, small-signal midband AC analysis, frequency response, large-signal AC performance, and digital circuits in different chapters, I emphasize the models, methods, and motivation for each type of analysis. Where possible, one example will be used throughout several chapters so, for example, you can learn about the DC biasing, midband gain, frequency response and large-signal swing of a common-emitter amplifier using a single example circuit. But the distinctions between the different types of analyses are emphasized by having each of them in a different chapter.

One feature of this text is the use of a generic transistor to present many of the basic principles that are common to FET and BJT circuits. While this transistor is fictitious, the terminal names used focus attention on the *functionality* of the device and the models used are the same as real transistors. The advantages of using this slight fiction are:

1. It helps to develop intuition about the operation of a given type of circuit without reference to the active device used (for example, a common-emitter BJT amplifier, common-source FET amplifier and even a common-cathode vacuum tube amplifier have much in common).
2. It allows common information to be presented once without dictating which type of transistor is covered first.
3. It helps to foster a modern device-independent way of thinking about circuits.

With this mode of thinking, the designer first considers the functionality of the circuit and then considers which type of device is best suited to a given application.

Another feature of this text is that it often breaks complex topics up into different levels of coverage to enable an instructor to decide how much detail to cover on a given topic at a given time. For example, most sections in Chapter 2 describing the operation of solid-state devices have an intuitive description followed by a more detailed derivation of the equations. The intuitive description can be used by students who have already had—or will have—a more detailed course in device physics. The detailed derivations can be used by students who have only one course covering electronic circuits and devices. As another example, the frequency response chapter presents both first-order methods for estimating the bandwidth of simple circuits (e.g., the Miller effect) and the more general zero-value time constant method. The more advanced zero-value time constant method may be left out of an introductory course taken by general Electrical and Computer Engineering students and can then be added in during a second-term course for students specializing in the circuits area.

One other feature of this text is that full solutions are provided for the exercises, rather than just numerical answers. It is my belief that if an exercise is involved enough to be of any real use to the student, simply providing the numerical answer is insufficient.

The final major feature of this text is the use of Asides. Asides are used for two different purposes. Sometimes, they are used to present material that is essential, but the student may already know from a prerequisite course, or may want to refer to later. Having the material in a separate Aside allows students to skip it or easily refer to it later. Asides are also sometimes used to present optional material that may expand on or further explain the material covered in the section. A separate index is provided to the Asides.

The CD that accompanies this text is also important. In addition to containing an evaluation version of the MicroSim DesignLab 8 software, which includes PSPICE, a postprocessor (PROBE), and a schematic capture program, the CD also includes all of the simulation files for over 100 exercises, examples, figures, and comments in the text. There are indexes on the CD for these files so that you can find, for example, a simulation file that shows how to use PSPICE to find the input or output resistance of an amplifier. In addition, the CD contains companion sections for a few places in the text where material was not printed for the sake of brevity (including two appendixes). I felt that some students would want this material.

There is more than enough material in this text for a two semester or three quarter sequence in electronic circuit design. Several different instructors have used drafts of this text for a two-quarter sequence at the University of California at Davis for several years. The first quarter of that sequence is required of all Electrical and Computer Engineering majors and covers Chapters 1 and 6, parts of Chapters 2, 7, and 8, the introductory material in Chapter 9, Chapter 14 and part of Chapter 15. The second quarter then adds the zero-value time constant method in Chapter 9, covers all of Chapter 10 and some of Chapters 4, 12, and 13. The material in Chapters 5 and 11 is used as reference material in other courses and Chapter 3 is left for the students to read, if they are interested.

Acknowledgments

Writing this book has been a *very* long process, and there are so many people to thank that I am sure I will forget someone. So, whoever you are, I ask your forgiveness in advance. To begin with, I thank my wife, Patti, and my children, David, Andrew, and Elizabeth, for putting up with hearing "when the book gets done" far too many times. I would next like to thank the many students who almost universally exhibited great patience while using early versions of the manuscript. I owe a debt of gratitude to the excellent teachers I have had the pleasure of learning from. I particularly want to thank Professor Artice M. Davis of San Jose State University and James D. Plummer of Stanford University, they are the finest two teachers I had when I was a student, and I am privileged to call them both friends. I would also like to thank Dr. Bruce M. Fleischer of IBM and Professor Thomas W. Matthews of Sacramento State University, who as students and friends have contributed to my own understanding of electronic circuits. It is a joy to work with Professors Stephen H. Lewis and Paul J. Hurst of UC Davis, they have both helped to make the Solid-State Circuits Research Laboratory an enjoyable place to work and learn. I also thank Dave Crook, Graham Baskerville, and John Steininger of National Semiconductor, and Ron Guly of HP, who were all helpful in providing data, photographs and other information that helped with this project. Dwight Morejohn helped tremendously with the cover art and Zoe Marlowe took the photograph for the Chapter Four opening figure. Professor James D. Plummer, Dr. Michael D. Deal and Dr. Peter B. Griffin were kind enough to allow me to extract material from their book, *Silicon VLSI Technology; Fundamentals, Practice, and Modeling*, to write Chapter 3—thanks! Professor Venkatesh Akella provided some of the information on digital CAD tools in Chapter Four. Charles Blas wrote the installer for the CD. Many students helped with problem solutions and reviewing the text; Salma Begum, Stephen Bruss, Efram Burlingame, Nick Chang, Chieu Yin Chia, Michael Collins, Ozan Erdogan, Alex Gros-Balthazard, Royce Higashi, Tunde Gyurics, Chris Holm, Yardley Ip, Jessi Johnson, Frank Lau, Tom McDonald, and Sophia Tang. In addition, Professor Thomas Matthews provided some of the problems and solutions. I am also grateful to the many reviewers who took the time to constructively comment on the text; Alok K. Berry from George Mason Universiy, Amir Farhat from Northeastern University, Samuel J. Garret from the University of South Florida, Rhett T. George from Duke University, Can E. Korman from the George Washington University, Sam Kozaitis from Florida Institute of Technology, Thomas Matthews from California State University Sacramento, Venkata Rao Mulpuri from George Mason University, Dennis Polla from the University of Minnesota, B. Song from San Jose State University, Karl A. Spuhl from Washington University, and John Uyemura from the Georgia Institute of Tehnology. I want to thank Tom Robbins, Scott Disanno, and the fine staff at Prentice Hall for putting up with me, keeping a sense of humor, and working hard to make the book as good as possible.

RICHARD SPENCER,
Davis, CA

About the Authors

Richard R. Spencer received the B.S.E.E. degree from San Jose State University in 1978 and the M.S. and Ph.D. degrees in Electrical Engineering from Stanford University in 1982 and 1987, respectively. He is a senior member of the IEEE.

He has been with the Department of Electrical and Computer Engineering at the University of California, Davis, since 1986, where is he is currently the Vice Chair for Undergraduate Studies and the Child Family Professor of Engineering. His research focuses on analog and mixed-signal circuits for signal processing and digital communication. He is an active consultant to the IC design industry.

Professor Spencer has won the UCD-IEEE Outstanding Undergraduate Teaching Award three times. He served on the IEEE International Solid-State Circuits Conference program committee for nine years, has been a guest editor of the IEEE Journal of Solid-State Circuits and has been an organizer and session chair for various IEEE conferences and workshops.

Mohammed S. Ghausi received the B.S.E.E., M.S. and Ph.D. degrees in Electrical Engineering from the University of California at Berkeley. He is a Professor Emeritus of Electrical and Computer Engineering as well as Dean Emeritus of the College of Engineering at UC Davis. His research interests are in electronics circuits and systems, and network theory, and he is the author or co-author of six textbooks. He was formerly a Professor of Electrical Engineering at New York University and later John F. Dodge Professor and Dean of Engineering and Computer Science at Oakland University. He is a recipient of the Alexander von Humboldt Prize, the IEEE Centennial Medal, the Circuits and Systems Society's 1991 Education Award, and the 1988 Outstanding Alumnus award of the Department of Electrical Engineering and Computer Science at the University of California at Berkeley.

Abbreviations, Acronyms, and Prefixes

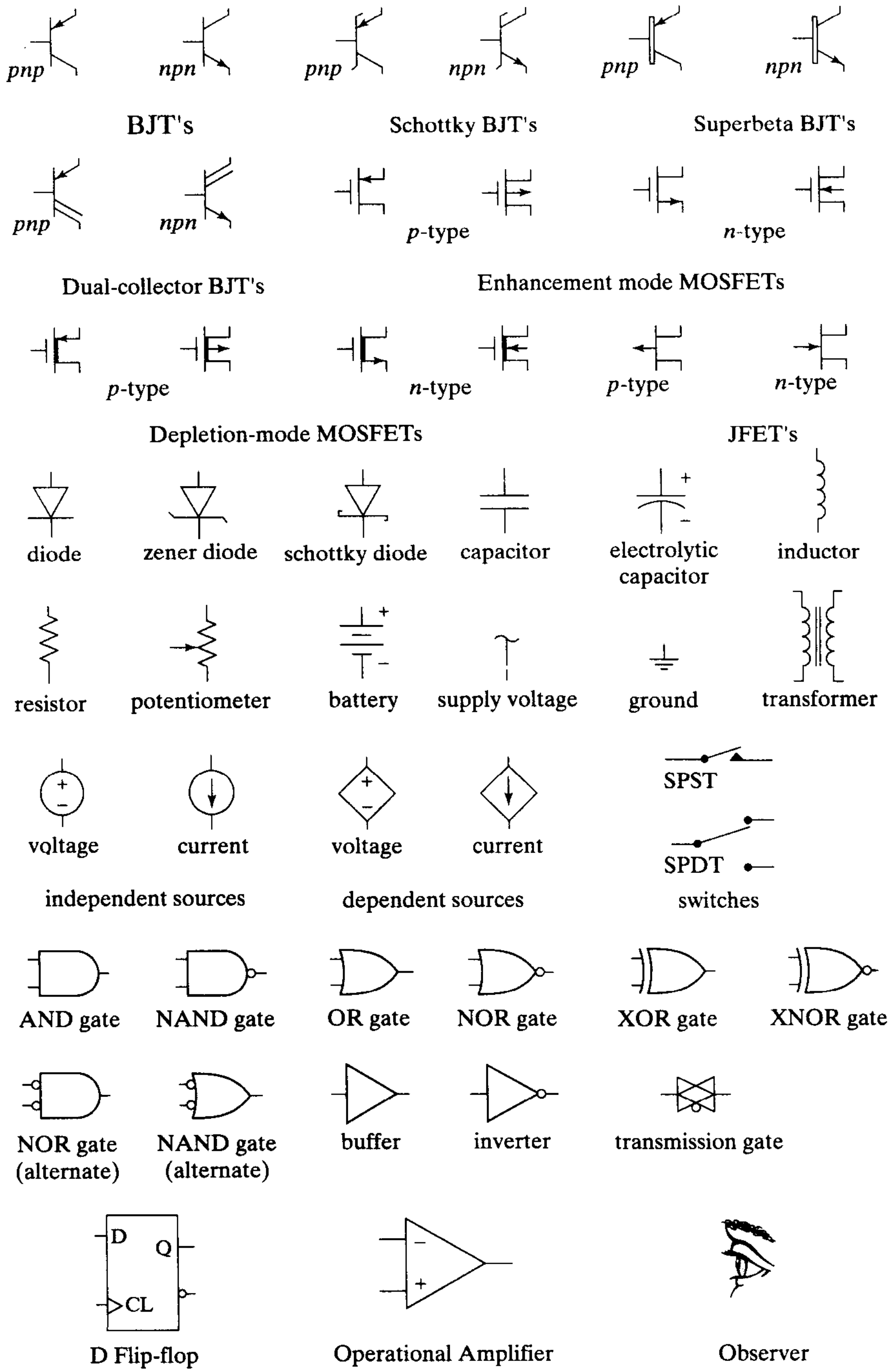
AC	Alternating current (i.e., changing with time - usually used for anything that isn't DC, so it really doesn't have to alternate in direction)
ADC	Analog-to-digital converter
AGC	Automatic gain control
AM	Amplitude modulation
ASCII	American standard code for information interchange
ASIC	Application specific IC
ASP	Analog signal processing
BCD	Binary-coded decimal
BER	Bit error rate
BJT	Bipolar junction transistor
BiCMOS	Bipolar and CMOS
BL	Bit line, or buried layer
BPF	Band-pass filter
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CBJ	Collector-base junction
CCCS	Current-controlled current source
CCVS	Current-controlled voltage source
CD	Compact disc
CML	Current-mode logic
CMOS	Complementary metal oxide semiconductor
CMP	Chemical-mechanical polishing
CMRR	Common-mode rejection ratio
CPU	Central processing unit
CVD	Chemical vapor deposition
DAC	Digital-to-analog converter
DC	Direct current (i.e., constant magnitude and direction)
DNL	Differential non linearity
DRAM	Dynamic RAM
DSP	Digital signal processing
DTL	Diode-transistor logic
DUT	Device under test
EBJ	Emitter-base junction
ECL	Emitter-coupled logic
EHP	electron-hole pair
EPROM	Erasable PROM
EEPROM	Electrically erasable PROM
EXOR	Exclusive OR (logic gate)
FET	Field-effect transistor
FIR	Finite impulse response
FFT	Fast Fourier transform
FM	Frequency modulation
FOM	Figure of merit
GaAs	Gallium Arsenide
GBW	Gain-bandwidth product
GIC	Generalized impedance converter
GTO	Gate-turn-off thyristor
HEMT	High-electron mobility transistor
HPF	High-pass filter
HVAC	Heating, ventilating, and air conditioning
IC	Integrated circuit
IF	Intermediate frequency
IGFET	Insulated-gate field-effect transistor
INL	Integral non linearity
JFET	Junction field-effect transistor
KCL	Kirchoff's current law
KVL	Kirchoff's voltage law

LDD	Lightly-doped drain
LED	Light-emitting diode
LO	Local oscillator
LOS	Line of symmetry
LPCVD	Low-pressure CVD
LPF	Low-pass filter
LSB	Least significant bit
LSI	Large-scale integrated circuit
LTI	Linear time invariant
MESFET	Metal-semiconductor field-effect transistor
MODFET	Modulation-doped field-effect transistor
MOS	Metal-oxide semiconductor
MOSFET	Metal-oxide semiconductor field-effect transistor
MSB	Most significant bit
MSI	Medium-scale integrated circuit
MTBF	Mean time between failures
NAND	Not AND (logic gate)
NMOS	N-type MOS
NOR	Not OR (logic gate)
npn	Negative-positive-negative (a type of BJT)
PCB	Printed circuit board
PDP	Power-delay product
PIV	Peak inverse voltage
PLL	Phase-locked loop
PMOS	P-type MOS
pnp	Positive-negative-positive (a type of BJT)
pot	Potentiometer
ppm	Parts per million
PROM	Programmable read-only memory
PSRR	Power-supply rejection ratio
RAM	Random-access memory
RC	Resistor and capacitor
RF	Radio frequency
RLC	Resistor, inductor, and capacitor
ROM	Read-only memory
RTL	Resistor-transistor logic or register transfer level
SAR	Successive approximation register
SCR	Silicon controlled rectifier
SNR	Signal-to-noise ratio
SOA	Safe operating area
SPICE	Simulation Program with Integrated Circuit Emphasis
SPDT	Single pole double throw (a kind of switch)
SPST	Single pole single throw (a kind of switch)
SR	Slew rate or set-reset (a type of flip flop)
SRAM	Static RAM
STTL	Schottky TTL
TC	Temperature coefficient
TTL	Transistor-transistor logic
VCCS	Voltage-controlled current source
VCO	Voltage-controlled oscillator
VCR	Voltage-controlled resistance
VCVS	Voltage-controlled voltage source
VLSI	Very-large-scale integrated circuit
VTC	Voltage transfer characteristic
WL	Word line
$R_1 \| R_2$	the notation means that R_1 is in parallel with R_2

The standard engineering prefixes used in this book are shown below.

Prefix	**Symbol**	**Value**
femto	f	10^{-15}
pico	p	10^{-12}
nano	n	10^{-9}
micro	μ	10^{-6}
milli	m	10^{-3}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}

Schematic Symbols



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