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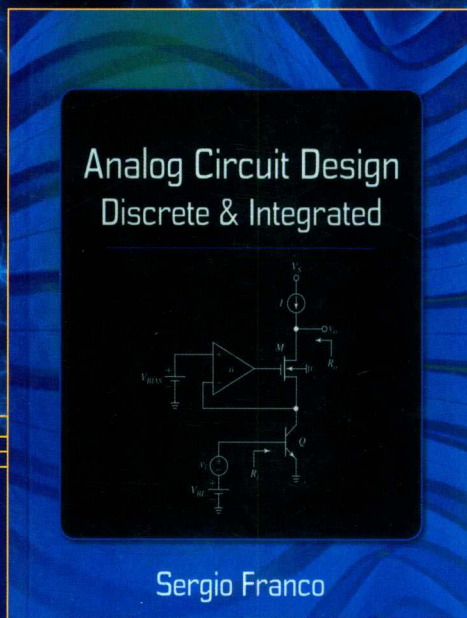
分立与集成

(英文版)

[美] Sergio Franco 著

雷鑑铭 注释

*Analog Circuit
Design
Discrete & Integrated*



机械工业出版社
China Machine Press

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图书在版编目 (CIP) 数据

模拟电路设计：分立与集成 (英文版) / (美) 弗兰克 (Franco, S.) 著；雷鑑铭注释。
—北京：机械工业出版社，2015.1

(国外电子与电气工程技术丛书)

书名原文：Analog Circuit Design: Discrete & Integrated

ISBN 978-7-111-48932-0

I. 模… II. ① 弗… ② 雷… III. 模拟电路—电路设计—英文 IV. TN710.02

中国版本图书馆 CIP 数据核字 (2014) 第 303200 号

本书版权登记号：图字：01-2014-7781

Sergio Franco: Analog Circuit Design: Discrete & Integrated (ISBN: 978-0-07-802819-9).
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出版发行：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：谢晓芳

责任校对：殷虹

印刷：北京瑞德印刷有限公司

版次：2015 年 1 月第 1 版第 1 次印刷

开本：186mm × 240mm 1/16

印张：53.75

书号：ISBN 978-7-111-48932-0

定价：119.00 元

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投稿热线：(010) 88379604

购书热线：(010) 68326294 88379649 68995259

读者信箱：hzjsj@hzbook.com

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本书法律顾问：北京大成律师事务所 韩光 / 邹晓东

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、Elsevier、John Wiley & Sons、CRC、Springer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Thomas L. Floyd、Charles K. Alexander、Behzad Razavi、John G. Proakis、Stephen Brown、Allan R. Hambley、Albert Malvino、Mark I. Montrose、David A. Johns、Peter Wilson、H. Vincent Poor、Dikshitulu K. Kalluri、Bhag Singh Guru、Stephane Mallat等大师名家的经典教材，以“国外电子与电气工程技术丛书”为总称出版，供读者学习、研究及珍藏。这些书籍在读者中树立了良好的口碑，并被许多高校采用为正式教材和参考书籍。其影印版“经典原版书库”作为姊妹篇也越来越多被实施双语教学的学校所采用。

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Preface

This textbook is intended for EE majors envisioning industrial careers in analog electronics. Analog integrated-circuit designers, product/process/reliability engineers, test/test-development engineers, and analog applications/marketing/customer-support engineers are always in great demand. The book is the result of my teaching experience at San Francisco State University, where over the years I have contributed to the formation of hundreds of students now gainfully employed in Silicon Valley in a wide range of analog positions. Here are three important features of this book:

- Both *bipolar* and *CMOS* technologies are covered. Even though digital electronics is dominated by CMOS technology, analog electronics relies on both CMOS and bipolar, the latter being the technology of choice in high-quality analog circuits as well as a fundamental part of BiCMOS technology.
- Both *discrete* and *integrated* designs are covered. Though nowadays the ultimate form of an analog system is likely to be of the integrated-circuit type, testing and applications often require ancillary functions such as conditioning and interfacing that are best realized with ad-hoc discrete designs. (Anyone familiar with the work by recognized leaders in analog applications/testing/instrumentation like Jim Williams and Robert Pease will agree to this.) In this respect, BJTs are available in a wide selection of off-the-shelf discrete types to serve a variety of needs, including practical experimentation in the lab. Moreover, for pedagogical reasons it is convenient to cover simple discrete circuits before tackling the more complex integrated circuits.
- *Semiconductor theory* is presented in sufficient depth to reflect the daily needs of a practicing engineer in industry. Every analog function is inextricably rooted on a physical phenomenon, so analog engineers, particularly IC designers and product/process/reliability engineers, need to be conversant with the physics of semiconductors in order to function optimally.

BOOK ORGANIZATION

The book is organized into two parts:

- The first part covers (1) *Diodes*, (2) *BJTs*, and (3) *MOSFETs*; as such, it is suited for a *first course in electronics*, typically at the junior level. The material is sequenced according to the technological evolution of electronics. However, the instructor who wishes to change the order of coverage of BJTs and MOSFETs can easily do so, as the two chapters are autonomous. Regardless of the order, the last chapter in the sequence can be covered much faster than the previous one as the student has already faced the challenges of dc biasing and large/small signal modeling.

- The second part covers (4) *Analog IC Building Blocks*, (5) *Representative Analog ICs*, (6) *Frequency and Time Responses*, and (7) *Negative Feedback, Stability, and Noise*. This part is suited for a *junior/graduate-level course in analog IC analysis and design*. In this part, BJTs and MOSFETs are mostly covered *side by side* so as to offer a unified treatment emphasizing similarities while recognizing inherent differences.

Each chapter provides a fairly comprehensive coverage of its title subject, so chapters are of necessity long (>100 pages each). The overall amount of material exceeds that of a typical two-semester or four-quarter course sequence, so the instructor has considerable leeway in material selection. Also, the author feels that the student needs to fully master low-frequency circuits before proceeding to the more challenging frequency and time responses of Chapter 6. But, the instructor can modify the coverage by skipping suitable topics from Part I in favor of selected topics from Chapter 6.

As mentioned, the first part focuses on basic transistor circuits emphasizing the more traditional *discrete design* approach. Pedagogically, it makes sense to study single-transistor circuits before progressing to multi-transistor systems—so much the better if this part is accompanied by a lab, where it is easier to investigate simpler circuits. In fact, at this level, a lab (complete with smoke!) is likely to offer a far more valuable learning environment than a computer-simulated one. A notorious drawback of discrete circuits is the need for coupling/bypassing capacitors, which introduce an element of additional distraction as it takes time for the student to develop full confidence with these capacitance functions. Cognizant of this, I have tried to demystify capacitors via detailed visual examples (see Fig. 2.55, p. 181, and Fig. 3.60, p. 302).

Following discrete circuits, the book progresses to *integrated circuits*. The integrated and discrete approaches are contrasted in Section 4.1; also, an intuitive borderline between the two is discussed in Exercise 4.3, p. 357. The second part progresses in complexity as well as sophistication from building blocks, to representative analog ICs, to IC dynamics, and finally to IC operation in negative-feedback, along with stability considerations, frequency compensation, and noise. This part is intended for IC designers but also for all other categories of engineers involved in fabrication, test, and applications. Application engineers, by far the largest group, need a working familiarity both with the technology (in order to make educated selections) and with the IC's inner functioning (in order to optimize its application). The book's aim is to promote a balance between the ability to *design on chip* and the ability to *design on board*.

The book website features a solutions manual and PowerPoint lecture slides for instructors as well as a list of helpful web links and errata. The author appreciates being notified of any possible errata.

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MOTIVATION

After having experimented with a number of other textbooks, I decided to write my own in response to a number of student concerns and also to implement my own ideas on how to better serve the needs of our graduates, who generally pursue careers in industry. Following are the most common student concerns:

- *Need to see lots of examples, especially of the type practicing engineers face daily.* I have painstakingly thought out each in-text example and end-of-chapter problem to serve two broad needs: to help the student develop a *feel* for the orders of magnitude of the quantities under study (see, for instance, Example 1.8, p. 42), and to deepen student *understanding* by following a circuit's evolution through different states or through increasing levels of complexity (see Figs. 1.18–20, pp. 16–17). In this respect, I made a concerted effort to develop a *systematic problem-solving methodology* emphasizing *thinking* and *physical intuition* as opposed to rote calculations. For it is in physical understanding, not in mathematical manipulations or computer simulations, that is rooted the design creativity the student will be called to exercise on the job. The book contains valuable rules-of-thumb working engineers use daily (see pp. 50, 52–55). Whenever possible, the student is reminded to use intuition and physical insight to anticipate what to *expect* from calculations or computer simulations, and to *check* results against physical substance (for physical insight see Example 6.5, p. 583, and Fig. 793, p. 787).
- *Incorporate SPICE simulation within the text.* SPICE has been integrated throughout the text both as a *pedagogical aid* to confer more immediacy to a new concept (see Fig. 4.66, p. 424), and as a *validation tool* for hand calculations. If unreasonable discrepancy is found between calculations and simulations, the student is challenged to account for possible causes (see Example 5.2, p. 490). Finally, SPICE is used to bring out nuances that would be too complex for hand calculations (see Example 6.11, p. 602). Nowadays a plethora of SPICE versions are available. Rather than committing to a particular version, I have decided to keep schematic capture circuits simple enough for students to set them up in their preferred SPICE version in a matter of minutes.
- *Provide practical exposure to basic semiconductor concepts.* The majority of graduates from my own institution (a state university) pursue industrial careers spanning a wide range of positions from IC designers to product and reliability engineers, test and test-development engineers, and application and customer-support engineers, where a broad background is far more desirable than a narrow specialization. A basic understanding of semiconductor principles is an integral component of such a background, especially for future product and reliability engineers.
- *Make generous use of figures* to comply with today's visually oriented learning trends. Most figures consist of two or more components placed side by side to visualize different facets of the same concept, be they different states of a circuit, or models, or time frames, or cause-effect relationships (see Fig. 1.59, p. 69). Also, the most relevant formulas intervening in a given analytical process have

been boxed for easy visualization, especially when the student crams for quizzes and tests. When appropriate, entire groups of formulas have been tabulated to facilitate their comparison (see Fig. 3.50, p. 289).

I tried to address the above concerns by returning to an essential, no-frills, no-distractions textbook format. Each chapter starts with a brief historical background and motivational framework, followed by a brief outline of the topics to be covered, followed by the chapter body proper. It concludes with a variety of carefully thought-out problems emphasizing intuition and physical insight.

THE CONTENTS AT A GLANCE

Chapter 1 starts out with the *ideal diode* as a vehicle for introducing the student to nonlinear circuit analysis and applications. This is followed by a review of the *operational amplifier* to pave the way for additional applications of diodes and, later, transistors. It is now time to introduce the student to the most common physical device approximating the diode function, the *pn junction*. After an intuitive review of *semiconductors*, the *pn junction* is discussed in proper detail, using *rules of thumb* to highlight those practical aspects that engineers use daily on the job. Working familiarity with the *pn junction* is crucial for the understanding of transistor physics in the following two chapters. Finally, various *popular diode applications* are discussed, often using PSpice as a pedagogical aid to enhance understanding.

Chapter 2 introduces the *bipolar junction transistor* (BJT) as a technological (and historical) evolution of the *pn junction*. Mirroring Chapter 1, we start out with the *physical structure* of the BJT, followed by the derivation of its *i-v characteristics*, the development of *large- and small-signal models*, *dc biasing*, and finally the analysis and design of *single-transistor amplifiers* and *buffers*. The common-emitter configuration is presented as the natural realization of voltage amplification, whereas the common-collector and common-base configurations serve most naturally as voltage and current buffers, respectively. Great emphasis is placed on the role of the BJT as a *resistance transformation device* (which actually provided the basis for its very name.) The transformation equations are conveniently tabulated for easy reference in later chapters.

Chapter 3 covers the MOSFET in similar fashion as the BJT of Chapter 2. However, the two chapters are kept independent of each other, so the order of coverage can be interchanged if desired. The chapter begins with a detailed discussion of the physical basis of the *native threshold* for the benefit of those students who will pursue careers as product, process, and reliability engineers. Next the MOSFET's *i-v characteristics* are derived, followed by the development of *large- and small-signal models*, *dc biasing*, and finally the analysis and design of *single-transistor amplifiers* and *buffers*. The common-source configuration is presented as the natural realization of voltage amplification, whereas the common-drain and common-gate configurations serve most naturally as voltage and current buffers, respectively. The chapter also covers the *CMOS inverter* and basic CMOS *logic gates* so as to provide a more balanced treatment for the benefit of computer engineering majors (see the PSpice noise-margin illustration of Fig. 3.44, p. 281).

Chapter 4 brings the student to a higher level of circuit sophistication by introducing the analog IC *building blocks* in widest use today. *Cascode* configurations, *differential amplifiers*, *current mirrors* of all types, *active loads*, and *push-pull output stages* are treated in proper detail in anticipation of their utilization in the following chapter. Whenever possible, BJTs and MOSFETs are covered side by side so as to present the reader with a *uniform treatment* and thus save space as well as effort.

Chapter 5 puts to use the blocks of Chapter 4 in the design of a *representative mix* of analog ICs in both bipolar and CMOS technologies, namely: *high-gain amplifiers* such as op amps, voltage comparators, and fully-differential op amps; *voltage and current references* such as bandgap references; *current-mode ICs* such as transconductors, OTAs, and current-feedback amplifiers; and, finally, *switched-capacitor circuits*.

Chapter 6 deals with the *frequency and time responses* of individual devices all the way up to complex circuits such as the ICs of Chapter 5. Frequency analysis relies on the *Miller approximation* as well as the *open-circuit time-constant technique*. The switching times of *pn diodes* and BJTs, unjustifiably ignored by current textbooks in spite of their enduring industrial relevance, are investigated via *charge-control analysis* emphasizing physical insight. Also covered are the *switching times of CMOS gates* for the benefit of computer engineering majors. This is a chapter in which in-text PSpice is put to frequent use as a verification tool for hand calculations.

Chapter 7 starts out with a comprehensive treatment of *negative feedback* as applied to the electronic circuits of all previous chapters, from single-transistor stages all the way to op amps. Both *two-port* and *return-ratio analyses* are presented and compared via a variety of carefully thought out examples. Also *Blackman's impedance formula* and *injections methods* are presented in a practical manner. The chapter proceeds to the subject of *stability* and *frequency-compensation* for op amps, both bipolar and CMOS (here again PSpice proves a most useful pedagogical tool). The chapter concludes with the study of noise in integrated circuits. After an introduction to basic noise properties, analytical tools, and noise types, the noise models of diodes and transistors are discussed. Finally, noise analysis is applied to representative circuit configurations such as op amp circuits and differential pairs.

A WORD OF ADVICE TO THE STUDENT

Your electronics courses provide the foundation for your career in EE. The objective of these courses is not only to introduce you to new devices such as *diodes* and *transistors*, but also to help you establish a *thinking style* and develop a *problem-solving methodology* that are unique to this challenging but most interesting field. Cognizant of the fact that a large proportion of EE graduates end up working in industry, I have emphasized those practical aspects that are of relevance in today's industrial milieu. Whether you pursue a career as an IC designer, a product engineer, a test or test-development engineer, or an applications or customer support engineer, the basic material of your first electronics courses will always resurface in a variety of ever-changing situations, so you may wish to invest far more time and effort in this one course than you would normally do—the benefits will be quite rewarding.

Even though diodes and transistors are *highly nonlinear* devices, special techniques have been developed for their analysis, which draw quite heavily from those covered in linear-circuits courses. Far from being a waste of time, the analytical tools learned in these prerequisite courses will be put to heavy use also in the study of electronics. Specifically, *Ohm's law*, *Kirchhoff's laws* (KVL and KCL), *Nodal/Loop Analysis*, *Thévenin's/Norton's theorems*, the *Superposition principle*, and the *Op Amp Rule* will continue to be valuable analytical tools as we venture into the exciting realm of electronics.

Electronics, like any other branch of engineering, deals with the *physical reality* of its devices and systems. We use mathematics as a *tool* to understand or predict their operation as well as to design new ones, and computer simulation as a verification tool. Any conceptual derivation or prediction must ultimately be checked against physical substance and never be taken for granted on its own. The use of physical reasoning to corroborate any conceptual process, be it a mathematical derivation or a computer simulation, is at the very core of this entire course sequence.

Beside proficiency in linear circuit analysis techniques, the student is expected to possess a working knowledge of basic calculus concepts, such as slope and area under a curve, as well as basic electrostatics concepts such as Gauss's theorem and the relations between electric field and potential. Also, the ability to perform circuit simulations via PSpice, as learned in prerequisite circuits courses and labs, will prove extremely useful for checking the results of hand analysis.

ACKNOWLEDGEMENTS

A number of reviewers provided detailed commentaries and many valuable suggestions. I tried to implement their recommendations whenever I could, but in the presence of conflicting viewpoints, I had to draw a line and pursue my own. To all who provided feedback, my sincere thanks. I would especially like to acknowledge Stephen Hubbard, Clemson University; Santosh Pandey, Iowa State University; and Donna Ginger Yu, North Carolina State University. Finally, I wish to express my gratitude to Diana May, my wife, for her encouragement and steadfast support.

Sergio Franco
San Francisco State University

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 - 1.9 正向偏置二极管特性
 - 1.10 *pn* 二极管电路的 DC 分析
 - 1.11 *pn* 二极管电路的 AC 分析
 - 1.12 击穿区域的应用
 - 1.13 DC 供电方式
- 附录 1A 二极管 SPICE 模型
- 参考文献
- 习题

二极管是最基本的电子器件。事实上，一个世纪以前，二极管的发明开创了电子时代。与电阻相似，二极管有两个端口；然而，与双向作用的电阻不同的是，二极管仅能单向传播电流。为了对这种特性有一个感性的理解，可以分析早期真空管类型的二极管。一个真空二极管包含一个发光的灯丝，称为阴极，作为提供自由电子的丰富源头；同时包含一金属板，称为阳极，去控制电流流动。在阳极上加入一相对于阴极的正向电压，将会吸引带负电荷的电子，从而保持电子从阴极向阳极的流动。相反地，在阳极上加入一反向电压，将会排斥电子，从而抑制电子流动。从水动力学

的分析角度来看, 二极管可以被形象化地比喻为一个单向阀门。

真空二极管是由 John A. Fleming 于 1904 年发明的。仅仅两年后, 在 1906 年, Greenleaf W. Pickard 发明了一种替代型的二极管, 是由形成一个对硅板的点接触制作而成的, 从而创造了第一个固态电子器件。然而, 半导体行业花费了半个世纪来投入商用, 所以真空管电子器件在 20 世纪的前半段是占主导地位的。

现如今的二极管由半导体材料制成, 与真空管器件相比, 它们在微型化、可靠性、能量消耗与成本等方面都有着极大的优势。具体而言, 虽然其他类的材料和结也有使用, 但是当今最普遍的二极管是硅 pn 结。 pn 结在微电子中起着关键性的作用, 不仅是因为其在各种应用的最底层提供二极管功能, 还由于其是双极型晶体管 (BJT)、结型场效应管 (JFET) 以及其他半导体器件如晶闸管 (SCR) 的基础。 pn 结也在金属-氧化物-半导体场效应晶体管 (MOSFET) 中出现, 这是当今电子产品中应用最广的器件。此外, 由于其反向偏置的特性, pn 结用于隔离共同存在于同一半导体芯片中的不同器件。

学习过线性电路预备课程的学生很快就会发现, 二极管以至于晶体管, 都是高度非线性器件。幸运的是, 众多的技术被研发出来以分析非线性器件, 它们从线性电路课程覆盖的范围内得到了很多方法。这并非浪费时间, 电路课程中学到的分析工具将在电子学的学习中起着重要的作用。具体来说, 欧姆定律、基尔霍夫定律 (KCL 与 KVL)、分压/分流定律、戴维南/诺顿定理以及叠加原理都将在我们探索激动人心的电子器件与系统领域时, 继续作为我们宝贵的分析工具。

本章重点 (Chapter Highlights)

本章开篇介绍理想二极管, 提出此概念以促进对二极管功能的基本理解, 同时介绍非线性电路的分析方法, 这是随后整个电子学的基础。应用包括二极管整流器、二极管逻辑门、电压钳位器、分段线性函数发生器、峰值检波器、直流复位器以及电压倍增器。

然后我们将回顾先修课程中基本运算放大器的原理, 因为二极管 (以及晶体管) 给运算放大器提供了广阔的应用范围。第一个二极管运算放大器应用将被认为是全波整流器, 其他的应用会随着我们的学习逐渐提及。

如前所述, 当今的二极管用半导体材料制成, 因此下一个目标是基本 pn 结理论的学习。在回顾完先修物理课程中普遍包含的半导体基础知识以后, 本章将对 pn 结进行直观的讨论, 特别强调那些与实用相关的方面 (经验法则) 知识点, 以形成现代工业环境中的电子工程师们需要的应用知识。无论学生是想成为 IC 设计师, 还是产品、加工或者可靠性工程师, 又或

者测试、应用工程师， pn 结将经常在各种情况下凸显其作用，因此仅适于我们在一定深度上进行研究。所有学生需要从基本物理学中记住的是高斯定理，以及电场与电势的关系，

$$\frac{dE}{dx} = \frac{\rho(x)}{\epsilon_{si}} \quad E = -\frac{dv(x)}{dx}$$

pn 结理论成果就是实际二极管的概念，尽管其与理想二极管有所偏差，但仍可以通过合适的线性方法进行分析。此处介绍二极管的大信号模型以及小信号模型，这些模型将在随后的章节中详述。

本章最后一部分将以上各种模型运用于若干实用电路如整流器、基准电压、基本非线性运算放大电路以及直流电源。附录讨论 SPICE 中二极管模型所涉及的参量。

作为典型的入门型课程，本章包括的材料内容比可行性分析内容可能要多。但是，教师可以轻易跳过特定的主题，如半导体理论的部分，特别是那些在其他课程中有所包含的部分。本章汇集了与二极管相关的所有（或绝大部分）内容。

1.1 THE IDEAL DIODE

The diode is a two-terminal device designed to conduct current in one direction only. Unlike the resistor, which conducts in either direction, the diode carries current only from the terminal called *anode* (A) to the terminal called *cathode* (C). Its circuit symbol, shown in Fig. 1.1a, uses an arrowhead to signify this directionality. The voltage across the diode is defined as positive at the anode and negative at the cathode, thus conforming to the *passive sign convention* of other popular devices such as resistors.

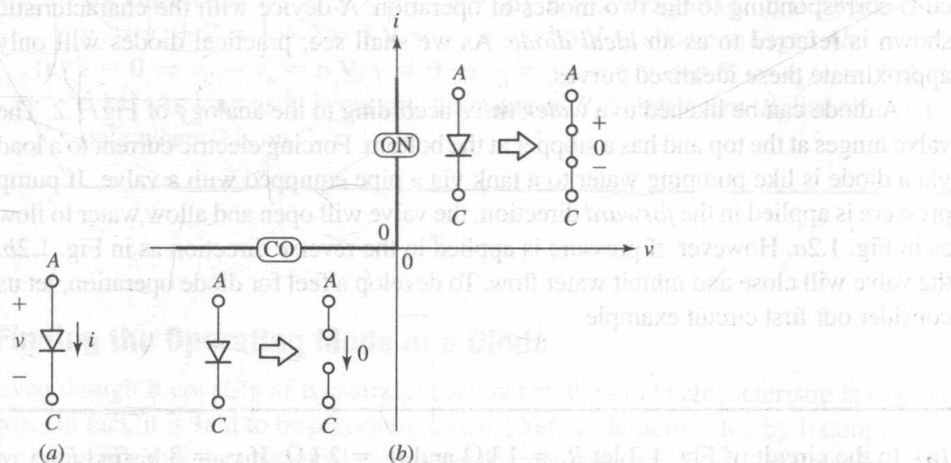


FIGURE 1.1 (a) Circuit symbol and sign convention for the diode. (b) Ideal-diode $i-v$ characteristic and diode models in the on (ON) region and in the cut-off (CO) region of operation.

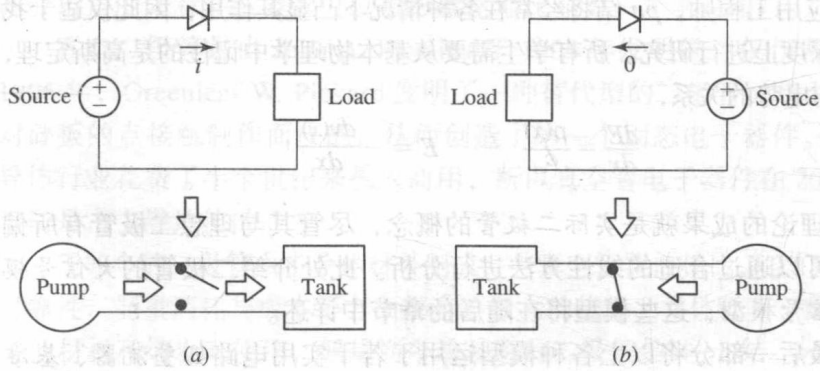


FIGURE 1.2 Valve analogy of a diode: (a) forward operation and (b) reverse operation.

When invited to draw current in the direction of its arrowhead ($i > 0$), also called the *forward* (F) direction, a diode will eagerly conduct the given current by acting as a *short circuit* ($v = 0$). In this case the diode is said to be *forward biased*, or also to be *on* (ON). However, if we try to force current in the opposite direction, also called the *reverse* (R) direction, the diode will stubbornly oppose current flow by acting as an *open circuit* ($i = 0$). The diode is now said to be *reverse biased*, or also to be *cut off* (CO). When cut off the diode will sustain whatever voltage ($v < 0$) is imposed by the surrounding circuitry.

Figure 1.1b shows the i - v characteristic of the diode, which we express mathematically as

$$v = 0 \quad \text{for } i > 0 \tag{1.1a}$$

$$i = 0 \quad \text{for } v < 0 \tag{1.1b}$$

Also shown next to the curves are the diode models (a short circuit and an open circuit) corresponding to the two modes of operation. A device with the characteristic shown is referred to as an *ideal diode*. As we shall see, practical diodes will only approximate these idealized curves.

A diode can be likened to a *water valve* according to the analogy of Fig. 1.2. The valve hinges at the top and has a stopper at the bottom. Forcing electric current to a load via a diode is like pumping water to a tank via a pipe equipped with a valve. If pump pressure is applied in the *forward* direction, the valve will open and allow water to flow as in Fig. 1.2a. However, if pressure is applied in the *reverse* direction as in Fig. 1.2b, the valve will close and inhibit water flow. To develop a feel for diode operation, let us consider our first circuit example.

EXAMPLE 1.1

- (a) In the circuit of Fig. 1.3 let $R_1 = 1 \text{ k}\Omega$ and $R_2 = 2 \text{ k}\Omega$. If $v_s = 3 \text{ V}$, find i_s so that D draws 1 mA . Show the final circuit.
- (b) If $i_s = 3 \text{ mA}$, find v_s so that D drops 2 V . Show the circuit.
- (c) If $i_s = 2 \text{ mA}$ and $v_s = 6 \text{ V}$, find R_1 and R_2 so that D operates at the origin of the i - v plane, where $v = 0$ and $i = 0$.