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英文版

[美] R. M. Warner
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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。

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Preface

Semiconductor-Device Electronics is a textbook designed for a core course on devices, a course that is usually offered in electrical-engineering and computer-science curricula during the junior year. The book was class-tested in nine quarters at the University of Minnesota before publication and has had a gratifying reception. This was a ten-week course, first in an electronics sequence. In ten weeks one can cover only the most basic material, and so the extension to a one-semester course would be easy. However, there is plenty of material in the textbook for a full year, so it is well adapted for use in a senior elective course or in a graduate program.

ORIGIN AND CONCEPT

We have seen an urgent need for a device-oriented electronics text of a particular kind. A student addressing this subject needs foundation knowledge that is extensive. Most electrical engineering (EE) students, at least, have been exposed to most of the necessary topics, but our experience indicates that for all but the most capable students, these topics remain at the fringes of understanding.

For this reason we have included foundation subject matter. This review material has been composed in a way that is consistent with a deeply held pedagogical conviction. *It proceeds from the specific to the more general.* The simplest, clearest example is given first as a stepping stone toward more complex cases. While a person of long experience in a subject can appreciate the elegance of a development that proceeds from the general to the particular, most newcomers cannot. Instead, they need specific and manageable components for constructing their own conceptual frameworks.

To illustrate our application of this principle, we can point to field theory.

Rather than starting with Maxwell's equations, we address a series of one-dimensional problems of a kind especially relevant to device theory. We stress the importance of gaining an intuitive, visceral understanding of Poisson's equation in these simple contexts and of some of the other, more elusive classical concepts such as electric displacement and dielectric-relaxation time. The device theory that is the subject of this book does not require us to go beyond one-dimensional descriptions, and space limitations do not permit it. But the theory provides a firm foundation for the student who subsequently faces two- and three-dimensional problems and situations requiring more general field theory. In a similar way, the Bohr atom is treated in terms that endeavor to relate electron behavior in an isolated atom to electron behavior in a crystalline solid.

Crystallography, on the other hand, is a topic that most EE students have not encountered before, but nonetheless it qualifies as a foundation topic in the sense that device engineers use its concepts almost daily. Additional fundamental subjects addressed are basic to all branches of engineering and science, but are often neglected. These include general problem-solving procedures and the skillful, consistent use of units.

Our primary aim in writing this textbook was to achieve clarity. We have made liberal use of analogies and heuristic descriptions and have avoided unnecessary jargon. In explanations, we have tried to choose a level that can be understood on first exposure. Intermediate equations have been included in most derivations so that the student can follow them easily, rather than deferring equation reading until "later."

One of the authors has taught device electronics to somewhat over 20 classes of EE juniors at the University of Minnesota and, in the same time interval, to 10 in-house classes for industrial firms at various locations throughout the country. Many of the university classes were large, numbering over 200 students, a factor that poses its own special problems. The least of these is speaking a bit more loudly or writing on the blackboard with larger letters.

As everyone who has had the experience knows, it is the administrative burden that is most troublesome with a very large class, even with adequate and competent assistance. Our book offers an important measure of relief in such a situation. It provides 229 analytic problems and an accompanying Solutions Manual. Given these analytic problems and solutions, one can choose the approach that fits the immediate situation best. The method frequently used, assigning problems and providing solutions later, is of course an option. But there is at least one other valuable option—an approach that we have used successfully for several years: Make the problems *and solutions* available to the students on the first day of class. Inform them that quiz and exam problems will be closely related to these, and that the students must therefore understand these problems and solutions thoroughly. This approach eliminates the burden of grading homework papers, which after the first offering of a particular course often becomes largely copied homework. (There are few academic activities that are more wasteful than the grading of copied homework.) This further frees the instructor to assign computer and design problems as homework.

In our experience, the approach of supplying both problems and solutions leads to a highly desirable focus on *understanding* on the part of the students. Discussion of problems and associated concepts dominates the recitation hours and student visits during office hours. To reinforce the instructor's serious intent in this regard, we often place a problem in an early quiz that is taken directly from the book, without even the alteration of numbers.

To use such a system, of course, the closed-book approach is necessary in quizzes and exams. This further reinforces the importance of understanding (rather than the skill of a file clerk). And this system does not make unfair or unreasonable demands upon a student's memory. The equations the students must know are extremely simple, typically involving only three or four symbols. If students truly understand, for example, that diffusive flux is proportional to density gradient, they can write down the relevant equation effortlessly. For more complex expressions, such as the continuity equations, we state the needed equation in the problem. Typically, the most complicated equations that we insist the student must know are the transport equations.

A further example along these lines is pertinent. The equations for depletion-layer thickness in various kinds of step junctions are important but can be looked up readily by engineers on the job. We consider memorizing these to be a relatively unprofitable investment of energy. But we *do* insist that students clearly understand that the depletion-layer thickness in *any* step junction varies as the square root of the potential difference between its two sides, and why this relationship exists. On this basis it is easy to devise problems that test understanding rather than memory. We have selected topics to emphasize fundamentals rather than state-of-the-art concepts. Only two major devices—the bipolar junction transistor and the MOS field-effect transistor—are addressed here because a thorough knowledge of these devices enables one to understand all other important IC devices. State-of-the-art devices are by their nature constantly evolving, and these changing facts are best learned on the job.

CONTENT AND ORGANIZATION

Chapter 1 presents the fundamentals of electricity in fresh fashion, as well as unit manipulation and problem solving, the Bohr model, and crystallography.

Chapter 2 treats equilibrium and nonequilibrium bulk properties of semiconductors, with silicon receiving heavy emphasis. It introduces band theory and explains how semiconductors, conductors, and insulators differ. The Fermi-level concept and its application is next, along with the most basic approximations frequently used in semiconductor work. The nature and consequences of "doping" lead into further fundamental equations and laws—mass action, the neutrality equation, and the Boltzmann relation. Carrier transport, recombination and generation, and the continuity equations for carrier-behavior analysis complete the chapter.

Chapter 3 deals comprehensively with the *PN* junction, at equilibrium and under bias. After the basic junction concepts are introduced, the depletion approximation is applied to a carefully selected sequence of examples and is subsequently expanded beyond step-junction cases. Static theory is augmented by a set of meticu-

lously recorded experimental data taken from the literature for the case of a particular silicon diode. The treatment of breakdown phenomena goes beyond the usual textbook treatment.

Unique to our book, however, is a new and integrated treatment of the dynamic properties of the *PN*-junction diode. It is used subsequently as the foundation for treating the dynamic properties of the BJT and the MOSFET. Also, a general treatment of step-junction and semiconductor-surface problems is included, which is found only in one other book. The high-low junction as ohmic contact is discussed—a feature found in vast numbers of semiconductor devices but ignored in most electronics textbooks. The principles of SPICE numerical analysis are given; in some cases, the detail presented exceeds that found even in SPICE manuals.

Chapter 4 offers BJT rudiments, basic device theory, biasing practice, and circuit-configuration options, stressing the properties of each. Structures and properties of real devices come next, followed by a detailed survey of high-level effects in the BJT. These effects are omitted from most texts, but because the BJT is routinely used under high-level conditions, this omission cannot be justified. Our section on the Ebers-Moll model stresses clarity and an appreciation of the physical significance of each step and is liberal with application examples. The small-signal-dynamic modeling of the BJT starts with the hybrid model, relating it to device physics, and proceeds through the hybrid-pi and other models, the charge-control model, and figures of merit. SPICE modeling is presented in unusual detail, large-signal and small-signal, with parasitic properties and thermal effects included.

Chapter 5 deals with the MOS capacitor and the MOSFET. After presentation of the elementary theory and inverter options, we describe the numerous phenomena that must be treated in an MOS capacitor. These are modeled carefully, using equivalent circuits and the general semiconductor-surface analysis introduced in Chapter 3. We include physical and analytic treatments of the capacitance-component interplay in the MOS capacitor and in the junction diode and then compare the two devices with respect to capacitive properties. Advanced modeling of the MOSFET follows, and the SPICE treatments of small-signal and large-signal problems follow that. The concluding section of the chapter, and of the book, is a new and detailed look at MOSFET-BJT performance comparisons that is not found in any other textbook.

LEARNING AIDS

Immediately following the text of each chapter are two features designed to provide a firm qualitative grasp of the subject matter. The first is a Summary that endeavors to encapsulate the essential elements of the chapter. The second is a set of review questions called "Topics for Review" (averaging 115 per chapter) that lets the student know very specifically whether key points have been mastered or, possibly, have been missed altogether. The most basic of the questions posed in this section are also useful for quiz and examination purposes.

An additional feature of our book is the in-text exercise and solution. On average about 60 of these appear per chapter. We have endeavored here to anticipate questions that could reasonably pop into the head of an alert reader. (We are eager to

obtain feedback on our success in reaching this goal.) Then the more aggressive or ambitious reader can ponder the issue and try to supply his or her own answer, before simply reading ahead into the solution.

There are other respects in which our book differs from most engineering texts. Topics in which spatial relationships are important are numerous in this subject area, with the space lattices of Chapter 1 providing a good example. In such cases, perspective drawings have been employed, replacing the primitive orthogonal-isometric drawings usually encountered.

Our accrediting agency, ABET, has in recent years placed a valid and growing emphasis on design skills, since engineers on the job do more synthesis than analysis. For this reason we have provided design problems at the end of each chapter in addition to the analytic problems discussed earlier. In a similar way and for similar reasons, computer problems also accompany each chapter, averaging more than two per chapter. Here we have selected problems *requiring* numerical treatment. In the last three chapters, these problems emphasize SPICE modeling. Normally we assign design and computer problems as homework. We have chosen to program the solutions using PASCAL, but other options are obviously available to the users of this book.

Finally, the Solutions Manual that accompanies our book has been prepared with unusual attention to legibility and accuracy. Of particular importance is the careful treatment of dimensions, a point stressed to reinforce the lesson on this subject in Chapter 1.

REFERENCE FEATURES

As much care and thoroughness have gone into assembly of the Subject Index as into the text material. It is unusually detailed, and important topics are liberally cross-referenced. While we can appreciate the fatigue factor that sometimes causes delegation of index preparation to nontechnical clerical people, we feel that extra effort invested here will enhance considerably the value of the book as a study and reference resource. In a similar vein, our policy on references has been to supply a substantial number, but far less than encyclopedic listings. (If a measure of chauvinism has crept into the selection process, we hope that our readers will be understanding.) We believe that the book will be used as a reference as well as a text. In summary, we have tried to select and emphasize the most basic and unchanging topics; then we have sought the clearest possible presentation. We hope that the result will provide entry to the eclectic discipline of solid-state-device electronics for many future students.

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R. M. Warner, Jr.
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