国外电子与通信教材系列

硅超大规模集成电路工艺技术：理论、实践与模型

Silicon VLSI Technology

Fundamentals, Practice and Modeling

英文版

James D. Plummer
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内容简介

本书是美国斯坦福大学电气工程系“硅超大规模集成电路制造工艺”课程所使用的教材，该课程是为电气工程系微电子学专业的四年级本科生及一年级研究生开设的一门专业课。本书最大的特点是，不仅详细介绍了与硅超大规模集成电路芯片生产制造相关的实际工艺技术，而且还着重讲解了这些工艺技术背后的科学原理。特别是对于每一步单项工艺技术，书中都通过工艺模型和工艺模拟软件，非常形象直观地给出了实际工艺过程的物理图像。同时全书还对每一步单项工艺技术所要用到的测量方法做了详细的介绍，对于工艺技术与工艺模型的未来发展趋势也做了必要的分析讨论。另外，本书每一章后面都附有相关内容的参考文献，同时还附有大量习题。

对于我国高等院校微电子学专业的教师及学生，本书是一本不可多得的优秀教材和教学参考书，并可供相关领域的工程技术人员学习参考。

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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

The silicon integrated circuit is surely one of the wonders of our age. The ability to fabricate tens of millions of individual components on a silicon chip with an area of a few cm^2 has enabled the information age.

Basic discoveries and inventions between 1945 and 1970 laid the foundations for these chips. In the past 30 years, chip complexity has increased at an exponential rate, primarily because of the constant shrinking of device geometries, improved manufacturing practice, and clever inventions enabling specific functions to be implemented in new ways. Shrinking geometries permit more devices to be placed in a given area of silicon; improved manufacturing permits larger chips to be economically fabricated; and clever inventions permit functions to be realized in smaller areas. It is widely expected that these historical trends will continue for at least another 10–20 years, resulting in chips that contain billions of components. Such chips will have extraordinary capabilities. We will likely find ourselves in 10–20 years thinking of today's chips as primitive precursors to the chips that will be in manufacturing at that time.

The technology that is used to build silicon integrated circuits today has evolved largely through empirical methods. It often seems that the chip industry moves so rapidly and new products are introduced so often that there is little time to worry about the scientific basis of the technologies used to build these chips. Yet in parallel with the rapid pace of this industry, a strong effort has been proceeding, often behind the scenes, to develop a solid, physically based understanding of the many technologies used in chip manufacturing. Because of the feature sizes of structures in modern chips, this understanding often needs to be on a molecular or atomic level. It is not sufficient any longer to think of silicon oxidation as simply a chemical reaction between silicon and oxygen that grows SiO_2. Today we must understand the detailed bonding between silicon and oxygen atoms and the kinetics that drive this reaction on an atomic basis.

Silicon integrated circuit technology makes use of many diverse fields of science and engineering. The optical steppers which print microscopic patterns on wafers, represent one of the most advanced applications of the principles of Fourier optics. Plasma etching involves some of the most complex chemistries used in manufacturing today. Ion implantation draws upon understanding from research in high energy physics. Thin films on the silicon wafer surface exhibit complex mechanical behavior which stretches our understanding of basic materials properties. And of course, silicon devices themselves are approaching physical sizes at which molecular and atomic scale phenomena involving ideas from quantum mechanics are important. One of the great challenges in integrated circuit manufacturing is the need to draw on scientific principles and engineering developments from such an extraordinarily wide range of disciplines. Integrating the knowledge from these diverse disciplines has been and will continue to be a great challenge. Scientists and engineers who work in this field need broad understanding and the ability to seek out, integrate and use ideas from many fields.

Over the past 20 years much has been learned about silicon and the other materials that are used in modern chips. Often new knowledge is incorporated in a "model" which may be a mathematical equation describing a process or an atomistic picture of how a particular process works. Models codify knowledge and are an elegant way of expressing what is known. They also provide a way of exchanging ideas between researchers in a particular field, and can be tested experimentally to assess their predictive capability.

Within the last decade, a serious attempt has been made to develop computer simulation tools which can simulate the various technologies used in fabricating chips. These simulation tools are built around models of the physical processes involved. Some simulation tools today use well-established scientific principles to predict experimental results. Optical lithography simulators, which are based on mathematical descriptions of Fourier optics, are a good example. Such tools today can accurately predict the image that will be printed in resist on a silicon wafer, given a particular mask design and a specific exposure system. Other simulation tools rest on less solid ground. Models of dopant diffusion in silicon, for example, use models which are still debated in the scientific community and which are clearly incomplete in terms of describing all the physical phenomena involved. Nevertheless, even these models are very useful today.

This book attempts to describe not only the manufacturing practice associated with the technologies used in silicon chip fabrication, but also the underlying scientific basis for those technologies. Those scientific principles are described in terms of models of the process in many cases. In most chapters, models are discussed in the context of computer simulation programs which have incorporated the models and which use them to simulate technology steps. We make extensive use of simulation examples to illustrate how technologies work and to help in visualizing features of the technologies that are not easily seen any other way. We have found these tools to be powerful teaching aids.

Simulation tools are widely used in the semiconductor industry today to supplement traditional experimental methods. While it is unlikely that simulation will completely eliminate the need for experiments, especially in a fast moving industry like the IC industry, simulators can result in very substantial cost savings in developing new generations of technology and in solving manufacturing problems. It is widely believed that simulation tools will be essential in the future if the rapid progress that has characterized the semiconductor industry is to continue.

This book is organized somewhat differently than other texts on this general topic, in two principal ways. The first is the extensive use of simulation examples throughout the text. These serve several purposes. The first is simply to help explain the scientific principles involved in each chapter. Simulations help to illustrate things like the time evolution of a growing oxide layer, a diffusing dopant profile or a depositing thin film. They are also very useful in illustrating the effects of specific physical phenomena in a process step because it is straightforward in simulators to add or eliminate specific physical models. Simulators provide the only real way in which complex interactions between process steps can be illustrated and understood. Finally, students who spend their careers in this industry will certainly use these tools and understanding their capabilities and limitations will be important in their future work.

The second way in which this book is organized differently is the discussion of a complete process flow early in the book (Chapter 2). While readers new to this field may not appreciate many of the complexities of a CMOS process before studying the later chapters, we have found that an early broad exposure to a complete chip manufacturing process is very helpful in establishing the context for the specific technologies discussed in later chapters. In teaching the material in this book, we usually cover the CMOS process in the first or second lecture somewhat superficially, and then return to the same topic in the last lecture, at which point the details can be more fully discussed.

We have also attempted in each chapter to include some discussion of future trends. Predicting the future is obviously difficult and there is some risk that including this material will simply serve to date this book. Nevertheless, we have found that students are often interested in this topic and at least in general terms, we believe it is possible to predict where silicon technology is heading. The semiconductor industry *National Technology Roadmap for Semiconductors* (the NTRS) provides some guidance in looking to the future.

The material in this book can be covered in a one quarter senior/graduate level course, although not all of the material in each chapter can be covered in one quarter. A semester long course would provide more time to cover the full range of material in the book. If the book is used in connection with a one quarter long course, one option is to minimize the amount of time spent on the Manufacturing Methods and Measurement Techniques sections in each chapter. A set of lecture notes based on figures from the text is available to instructors by contacting the publisher or the authors by email. We have used these notes several times in a one quarter course at Stanford.

Follow-on courses to a basic IC fabrication course can make more extensive use of the simulation tools discussed in this text. We have not used the simulation tools described in this book for homework assignments or for lab assignments in connection with a first course in IC fabrication. We believe that the simulation examples are better used simply as teaching tools in such courses, to illustrate ideas and to clarify physical principles. But in a follow-on course, hands-on experience with these simulation tools is easily possible. Most of the computer tools we use in the book are commercially available and the vendors of these tools are generally anxious to work with university instructors to make the tools available for teaching purposes.

Finally, we acknowledge the many students at Stanford who have helped refine the material in this book by using various draft versions of the text in classes we have taught. Their inputs and suggestions have hopefully made this a better book. For many years we have worked with an energetic group of Ph.D. students and faculty colleagues at Stanford who have helped to develop some of the models and software tools described in this book. We particularly acknowledge Professor Bob Dutton and former Ph.D. students Professor Mark Law (now at the U. Florida) and Dr. Conor Rafferty (now at Lucent Technologies). We are also very grateful to a number of individuals who reviewed draft versions of this book and who provided technical inputs to various chapters. Paul Rissman of Hewlett Packard, Jim McVittie of Stanford, and Mark Law all

provided substantial inputs and comments. Our own work in this field has been supported over many years by DARPA (the Defense Advanced Research Projects Agency) and by the Semiconductor Research Corporation (SRC) . We owe them a considerable debt of gratitude for making our work possible. We welcome comments or suggestions on this text by email at plummer@ee.stanford.edu, deal@ee.stanford.edu, or griffin@stanford.edu.

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