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Integrated Microelectronic Devices
Physics and Modeling

集成微电子器件

（英文版）

［美］ Jesús A. del Alamo 著

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内容简介

本书是MIT开放课程采用的教材，重要特点是以与现代集成微电子学相关的方式介绍半导体器件操作的基本原理，不涉及任何光学或者功率器件，重点强调集成微电子器件的频率响应、布局、几何效应、寄生问题和建模等。本书分为两部分，合计11章。第一部分（第1章至第5章）介绍半导体物理的基本原理，包括电子、光子和声子，平衡状态下的载流子统计特性，载流子的产生与复合，载流子的漂移和扩散，载流子运动，内容涵盖能带结构、电子统计、多数载流子和少数载流子等相关知识。第二部分（第6章至第11章）分别讲解pn结二极管、肖特基二极管和欧姆接触、硅表面和金属–氧化物–半导体结构、“长”金属–氧化物–半导体场效应晶体管、“短”金属–氧化物–半导体场效应晶体管，以及双极结型晶体管，详细探讨各种器件的物理机理及操作原理。各章涵盖了非理想条件、二阶效应及其他与实际器件相关的重要因素。全书的内容架构有利于学生的理论知识学习与未来工作实践的衔接过渡。

本书适合电子科学与技术、微电子及光学工程等专业的本科生或相关专业的研究生作为双语教材使用。

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Preface

Judging by its age, now beyond 50 years old, one would think that microelectronics is a mature engineering discipline. Yet, its youthful exponential growth and its dramatic impact on human society continue unabated. For those of us that have been given the privilege of playing a role in this amazing endeavor, it has been an exhilarating experience. For years it was predicted that the relentless down scaling of transistor dimensions will hit a "fundamental limit" beyond which traditional device physics will be irreparably upset and progress will stall. Fortunately, semiconductor technologists and device engineers have been too busy to listen to the doomsayers. Innovative solutions to the challenges that continued to emerge were identified. Old taboos and preconceptions had to go by the wayside, and new materials needed to be brought to bear but progress never slowed down. The "microelectronics revolution" is perhaps the best exponent of human creativity and resourcefulness that there has ever been.

While recently, expressions of concern about the impending end of "Moore's Law" have grown louder and the path forward with transistor scaling is not entirely apparent, it is very clear that CMOS (complementary metal–oxide semiconductor, a logic circuit family based on metal–oxide–semiconductor field-effect transistors) in whatever form it will take, will continue to be the backbone of computation, communications, power management, medical devices and many other kinds of systems for years to come. Also clear is that going forward, a richer set of technological options will need to be investigated: new materials, new structures, new geometries, and even new physics. In this context, indepth understanding of semiconductor fundamentals and device physics will be more valuable than ever.

It is in this regard that this book attempts to fill an important gap in the academic literature. While there are excellent texts on semiconductor device physics in themarket, there is a need for a rigorous description that is relevant to modern nanoelectronics. In recent times, for instance, the so-called "extrinsic effects" or "parasitics" have come to play a dominant role in device operation. Moreover, device physics such as impact ionization and breakdown represent significant considerations in nanoscale device design. Another example is the role of device layout on device performance metrics that is of increasing relevance. This book additionally aims to provide a realistic technology context for the main streamdevices: the metal–oxide–semiconductor field-effect transistor (MOSFET) and the bipolar junction transistor (BJT).

This book is based on my experience in teaching *6.720J/3.43J Integrated Microelectronic Devices*, a semester-long graduate student subject jointly offered in the Departments of Electrical Engineering and Computer Science (EECS) and Materials Science and Engineering (MS&E) at Massachusetts Institute of Technology (MIT). Typically, the class is composed of graduate students in EECS, Materials Science, Mechanical Engineering, Chemical Engineering and Physics plus a few seniors in the same departments. Graduate students in EECS and MS&E with interest in semiconductor materials and devices are strongly encouraged to take this subject their very first semester at MIT. While the book originated in a graduate course at MIT, it has been constructed to be productively used in an advanced undergraduate subject at the junior/senior level, as explained below.

The central goal of this book is to present the fundamentals of semiconductor device operation with relevance to modern integrated microelectronics (as opposed to, say, photonics, energy conversion devices, or power electronics). This means that no optical devices nor power devices of any kind are described. In contrast, emphasis is devoted to frequency response, layout, geometrical effects, parasitic issues and modeling in integrated microelectronics devices (transistors and diodes). In spite of this focus, the concepts learned here are highly applicable in other device contexts. This book should be a great resource for a broad range of students with a diverse set of interests.

There are two distinct parts to this book. The first five chapters introduce fundamental aspects of semiconductor physics pertaining to microelectronic devices: band structure, electron statistics, generation and recombination, drift and diffusion, and minority and majority carrier situations. Each chapter gives in its main body a general description suitable for a junior/senior-level or a first-year graduate course. These chapters also include at the end a number of advanced topics that can be selected individually to provide further depth. These can be the basis of a more advanced graduate subject.

Six device chapters follow with a similar outline. After a brief introductory section, the main body of the chapter presents a first-order, physically meaningful description of device physics and operation of an "ideal device". The ideal device is stripped down to its very essence, preserving the key physics, and is analyzed in a simple and intuitive way. The ideal device, constructed and studied this way, is therefore an excellent vehicle to learn device physics at the junior/senior level. One or more of the following sections present significant non idealities, important second-order effects and other considerations that are relevant in "real" devices. These are suitable topics for graduate courses. To some extent, teachers of graduate subjects will be able to pick and choose topics from these latter sections since they are rather independent of one another. Every chapter finishes with a set of advanced topics that contain more advanced graduate-level material also amenable to individual selection.

With this organization, the proposed text should be suitable for a one-semester junior/senior-level course by selecting the front sections of selected chapters (1 through 9 should be a popular set). At the same time, it could be used in a two-semester senior-level or a graduate-level course by taking advantage of the more advanced sections. In all cases, the book will provide plenty of reading material for personal study and future reference.

As required background for students to follow a course based on this book, in addition to freshman and sophomore physics and math, is a sophomore/junior subject on microelectronic circuits (at a level such as Sedra & Smith's *Microelectronic Circuits*). Specific essentials are basic linear and non-linear circuit understanding and an ability to work in the frequency domain. This book does not require previous knowledge of semiconductor device physics, quantum mechanics or statistical mechanics. It does however expect a certain degree of student sophistication in handling complexity, mathematical rigor, and physical intuition. This book will best serve students that have already taken a course that presents an integrated introductory view of devices and circuits, such as in Howe & Sodini's *Microelectronics: An Integrated Approach.*

This book would not have been possible without the help and support of many people. It was my MIT colleague Charles Sodini who encouraged me to launch this project in 1993 and gave me feedback and advice on its organization and on the content of many early chapters. Little did Charlie know, nor I, that this project would take the bulk of my career at MIT to complete. I inherited content and benefited from feedback and advice from several colleagues at MIT: Dimitri Antoniadis, Clifton Fonstad, Judy Hoyt, Tomás Palacios, and Stephen Senturia. The book includes specific materials generously contributed by a number of individuals: Phaedon Avouris, Douglas Buchanan, Massimo Fischetti, Matthew Fox, Paul Humphries, Sergei Krupenin,Wenjie Lu, Richard Martel, Samuel Mertens, Richard Molnar, Tassanee Payakapan, Brad Scharf, Shinichi Takagi, and Ling Xia. They are all identified at the appropriate location in the text.

My teaching assistants and students in 6.720J/3.43J supported me and encouraged me in this project over the years in numerous ways. I want to single out (apologies if I forget significant contributions!): Pablo Acosta, Tracy Adams, James Fiorenza, Iliana Fujimori, Usha Gogineni, David Greenberg, Alex Guo, Donghyun Jin, Jungwoo Joh, Dong-Seup Lee, Jianqiang Lin, Jelena Madic, Dennis Ouma, Jorg Scholvin, James Teherani, Anita Villanueva, Niamh Waldron, Chagarn Wang, Ginger Wang, Shireen Warnock, Joyce Wu, Mehmet Yanik, and Xin Zhao. I have also benefited from comments and feedback from many colleagues at MIT and beyond. Among them, I want to thank Thomas Clark, Emmanuel Crabbé, Isik Kizilyalli, Jody Lapham, Terry Orlando and Markus Zahn.

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Thanks are also due to the staff at Pearson and Prentice Hall that have supportedme through this project: Julie Bai, Scott Disanno, Tom Robbins, Shylaja Gattupalli, and Carole Snyder.

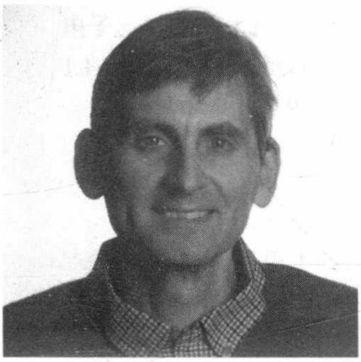
My passion for semiconductors was ignited by the opportunity that Prof. Antonio Luque gave me to become engaged in his research program on solar cells when I was an undergraduate student at Universidad Politécnica de Madrid in Spain. My mentor at Politécnica, Dr. Javier Eguren, patiently guided me through the very first steps of my research career. My PhD advisor at Stanford University, Prof. Richard M. Swanson, further nurtured my love for semiconductor devices through his vivid and insightful explanations of device physics. I owe an immense debt of gratitude to all three of them for their confidence in me and their encouragement over the years.

This book is dedicated to my sons, Diego, Paul, and Antoine. Writing it took a lot of time away from them. I hope they come to value the impact that this book can make on the careers of young people like themselves.

This project has been sustained by the patience and encouragement of Sophie, my wife. I am grateful for her presence in my life!

Jesús A. del Alamo

About the Author



Jesús A. del Alamo is Donner Professor and Professor of Electrical Engineering in the Department of Electrical Engineering and Computer Science at Massachusetts Institute of Technology. He is also Director of the Microsystems Technology Laboratories at MIT. He obtained a Telecommunications Engineer degree from the Universidad Politécnica de Madrid (Spain) and MS and PhD degrees in Electrical Engineering from Stanford University. From 1985 to 1988 he was with NTT LSI Laboratories in Atsugi (Japan). He joined MIT in 1988.

Over the years, Prof. del Alamo has been involved in research on transistors and other electronic devices in a variety of material systems. He has worked on Si solar cells, Si bipolar junction transistors, Si metal–oxide–semiconductor field-effect transistors (MOSFETs), SiGe heterostructure devices, GaAs pseudomorphic high electron mobility transistors (PHEMTs), InGaAs high electron mobility transistors (HEMTs) and MOSFETs, InGaSb HEMTs and MOSFETs, GaN HEMTs and MOSFETs, and more recently diamond MOSFETs. He has also investigated quantum-effect devices based on AlGaAs/GaAs heterostructures. His current research interests focus on the physics, technology, modeling and reliability of new III-V compound semiconductor field-effect transistors for future logic applications.He is also interested in fundamental reliability physics of GaN transistors for RF power amplification and power switching applications. In addition, Prof. del Alamo investigated the technology and pedagogy of online laboratories for science and engineering education (the iLab Project).

Prof. del Alamo's students have earned numerous best paper awards at national and international conferences. A paper from his group presented at the 2008 International Electron Devices Meeting (IEDM) was selected at the 60th Anniversary IEDM in 2014 as *One of the Ten Most Influential IEDM Papers of the Last Decade*. For his research on InGaAs quantum-well field-effect transistors, he was awarded the 2012 Intel Outstanding Researcher Award in Emerging Research Devices and the Semiconductor Research Corporation 2012 Technical Excellence Award.

Prof. del Alamo teaches undergraduate and graduate-level courses at MIT in electronics, electron devices and circuits, and advanced semiconductor device physics. He has received multiple teaching and achievement awards at MIT: the 1992 Baker Memorial Award for Excellence in Undergraduate Teaching, the 1993 H. E. Edgerton Junior Faculty Achievement Award, the

2001 Louis D. Smullin Award for Excellence in Teaching, and the 2002 Amar Bose Award for Excellence in Teaching. In 2003, he was named a MacVicar Faculty Fellow and in 2007, he was appointed Donner Professor. He has also been a recipient of the Class of 1960 Innovation in Education Award in three separate occasions. In 2012, Prof. del Alamo was awarded the IEEE Electron Devices Society Education Award "for pioneering contributions to the development of online laboratories for microelectronics education on a worldwide scale".

From 1991 to 1996, Prof. del Alamo was a National Science Foundation Presidential Young Investigator. He is also Corresponding Member of the Royal Spanish Academy of Engineering, Fellow of the IEEE and Fellow of the American Physical Society. In 2015, Universidad Politécnica de Madrid granted him a Doctor *Honoris Causa*.

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