## Understanding Modern Transistors and Diodes

Written in a concise, easy-to-read style, this text for senior undergraduate and graduate courses covers all key topics thoroughly. It is also a useful self-study guide for practising engineers who need a complete, up-to-date review of the subject.

**Key features:**

- Rigorous theoretical treatment combined with practical detail
- A theoretical framework built up systematically from the Schrödinger Wave Equation and the Boltzmann Transport Equation
- Covers MOSFETS, HBTs, HJFETS, solar cells and LEDs.
- Uses the PSP model for MOSFETS
- Describes the operation of modern, high-performance transistors and diodes
- Evaluates the suitability of various transistor types and diodes for specific modern applications
- Examines solar cells and LEDs for their potential impact on energy generation and reduction
- Includes a chapter on nanotransistors to prepare students and professionals for the future
- Rigorous treatment of device capacitance
- Provides results of detailed numerical simulations to compare with analytical solutions
- End-of-chapter exercises to aid understanding
- Online availability of sets of lecture slides for undergraduate and graduate courses

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# Preface

*Understanding Modern Transistors and Diodes* is a textbook on semiconductor devices with three objectives: (i) to provide a rigorous, yet readable, account of the theoretical basis of the subject of semiconductor devices; (ii) to apply this theory to contemporary transistors and diodes so that their design and operation can be thoroughly understood; (iii) to leave readers with a sense of confidence that they are well equipped to appreciate the workings of tomorrow's devices, and to participate in their development.

There are many books on semiconductor devices, often with similar objectives, and it is reasonable to ask: why write another one? The answer is two-fold: firstly, after teaching and researching in the area for 40 years, I have a strong personal viewpoint on how the subject can best be presented to students; secondly, we are at a particularly interesting point in the development of the subject – we are at the micro/nano boundary for high-performance transistors, and we are on the threshold of seeing optoelectronic diodes make a contribution to our planet's sustainability.

These circumstances are new, and are quite different from those of 20 years ago when I was last moved to write a book on semiconductor devices. At that time the major development was the incorporation of thousands of transistors into monolithic integrated circuits. To design and analyse such circuits, the transistors were represented by a set of model parameters. One could use these parameters to design a circuit without understanding how they related to the physical properties of the actual transistors comprising the circuit. To address this deficiency I co-authored a book with Garry Tarr in 1989 that specifically linked circuit-model parameters to the physical properties of transistors and diodes.[1]

Today, after a further 20 years of teaching and researching in the area of solid-state devices, I find myself lecturing on, and needing to know more about: the effect of miniaturization on the performance of silicon field-effect transistors, as used in increasingly dense integrated circuits and memories; the displacement of the silicon bipolar transistor from its traditional areas of strength (high-frequency, high-power, low-noise) by heterostructural devices based on compound semiconductors; how device engineers and physicists can address sustainability issues in their domain, particularly the generation of electricity from a renewable source via more cost-effective solar cells, and the reduction of electricity usage for lighting via high-brightness light-emitting diodes. Sometimes I feel as though the trends in semiconductor devices are creating

[1] D.L. Pulfrey and N.G. Tarr, *Introduction to Microelectronic Devices*, Prentice-Hall, 1989.

an impossible situation: the need for greater depth of knowledge in a wider variety of devices.

The solution to this dilemma comes back to the first objective of this book: provide a rigorous and digestible theoretical basis, from which the understanding of devices of the modern era, and of the near future, follows naturally. This is how *Understanding Modern Transistors and Diodes* meets the challenge of covering a wide breadth of topics in the depth they warrant, while managing to limit the material to that which can be covered in one or two one-term courses. The requisite physics is treated properly once and is then approximated, and seen to be approximated, where justifiable, when being applied to various devices. The physics has to be quantum mechanical for several reasons: band structure is important for all the devices we discuss, particularly for heterostructural diodes and transistors of both field-effect and bipolar varieties; electron-photon interactions are obviously relevant in solar cells and light-emitting diodes; tunnelling is an important leakage-current mechanism in field-effect transistors; future one-dimensional transistors may be so short that ballistic, rather than dissipative, transport will be operative. Even in 'classical' devices transport must be treated rigorously in view of the trends towards miniaturization: the Drift-Diffusion Equation cannot be blindly applied, but must be justified after a proper treatment of its parent, the Boltzmann Transport Equation. One intermediate solution to this equation, the charge-density continuity equation, provides the basis for our rigorous and formal description of capacitance. This device property is crucially important to the transistors presented in the application-specific chapters in the book on digital switching, high-frequency performance and semiconductor memories. As a final emphasis on the rigour of this book, the traditional SPICE-related model for the MOS field-effect transistor is put in its rightful place, i.e., as a computationally expedient approximation to the 'surface-potential' model. If SPICE has helped design circuits that have enabled higher performance computers, then that has been its downfall, because those computers can now permit the more rigorous surface-potential model to be used for the more accurate simulation of integrated circuits!

*Understanding Modern Transistors and Diodes* is intended for students at the graduate or senior-undergraduate level who are studying electronics, microelectronics or nanoelectronics, within the disciplines of electrical and computer engineering, engineering physics or physics. However, there is sufficient material on basic semiconductor theory and elementary device physics for the book to be appropriate also for a junior-level course on solid-state electronic devices. Additionally, the inclusion in the book of specific chapters on the application of the foundation material to modern, high-performance transistors and diodes, and a glimpse into the future of true nanotransistors, should make the book of interest to practitioners and managers in the semiconductor industry, particularly those who have not had the opportunity to keep up with recent developments in the field. It is my hope that the depth and breadth of this book might make it a 'one-stop shop' for several levels of courses on semiconductor devices, and for device-practitioner neophytes and veterans alike. The material in this book, in various stages of development, has been used by me for senior-level undergraduate courses and for graduate-level courses on semiconductor devices at UBC, for short courses to engineers at PMC-Sierra in Vancouver, and to graduate students at the University of Pisa and at the Technical

University of Vienna. I thank all those students of these courses who have commented on the material and have sought to improve it.

As an undergraduate I focused on 'heavy-current electrical engineering', and never benefited from a course on semiconductor devices. I am basically 'self-taught' in the area, and I think that this has attuned me particularly well to the nature of the difficulties many students face in trying to master this profound subject. Hopefully this book circumvents most of these obstacles to the understanding of how semiconductor devices work. If it does, then thanks are due to many people who have enlightened me over my 40 years of working in the subject area, both as a professor at the University of British Columbia, and as a visiting research engineer at various industry, government, and university laboratories around the world. I particularly want to mention Lawrence Young, who hired me as a postdoc in 1968, and thereby started my transformation to a 'light-current electrical engineer'. I owe a great debt of gratitude to my graduate students, with whom I have worked collegially, learning with them, and sharing the work 'in the trenches' as much as possible. One of the great pleasures of writing this book has been to call on some of them, and on some former undergraduates too, to make sure that the material in some of the device-specific chapters in the book is truly modern. Particularly, I wish to thank: Alvin Loke (AMD, Colorado) for his enthusiastic support, his insights into the finer points of modern, high-performance CMOS devices and his arrangement of the procurement of the cover photograph from AMD's Dresden laboratory; Tony St. Denis (Triquint, Portland) for provision of material on high-frequency and low-noise heterojunction field-effect transistors; Mani Vaidyanathan (University of Alberta) for his insights into high-frequency devices, and for his encouragement; Leonardo Castro (Qimonda, Munich) for helpful details on DRAMs; David John (NXP, Eindhoven) for useful information on silicon power transistors, and for alerting me to Philips' version of the MOSFET surface-potential model; Shawn Searles (AMD, Austin) for sharing his thoughts on where Si CMOS is heading; Gary Tarr (Carleton University) for commenting on the solar cell chapter. I also wish to thank Ivan Pesic of Silvaco Data Systems for making a copy of his company's excellent simulation software, Atlas, available to me during 2008. At Cambridge University Press, England, I thank Julie Lancashire for her encouragement of this project, and Sarah Matthews, Caroline Brown and Richard Marston for their assistance in bringing it to fruition.

Most 'part-time' authors of technical books comment on the interruptions to their family life that writing a textbook entails, and I am no exception. My children, their spouses and my grandchildren are my friends, and I am conscious of the time I have missed spending with them. I hope they will think that this book has been worth it. The writing of it has been sustained by the encouragement, support and understanding of my wife, Eileen, to whom I give my deepest thanks.

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