Introduction to Semiconductor Devices

For Computing and Telecommunications Applications

From semiconductor fundamentals to state-of-the-art semiconductor devices used in the telecommunications and computing industries, this book provides a solid grounding in the most important devices used in the hottest areas of electronic engineering today. The book includes coverage of future approaches to computing hardware and RF power amplifiers, and explains how emerging trends and system demands of computing and telecommunications systems influence the choice, design, and operation of semiconductor devices.

The book begins with a discussion of the fundamental properties of semiconductors. Next, state-of-the-art field effect devices are described, including MODFETs and MOSFETs. Short channel effects and the challenges faced by continuing miniaturization are then addressed. The rest of the book discusses the structure, behavior, and operating requirements of semiconductor devices used in lightwave and wireless telecommunications systems.

This is both an excellent senior/graduate text, and a valuable reference for engineers and researchers in the field.

Kevin Brennan (1956–2003) was the recipient of a National Science Foundation Presidential Young Investigator Award. He was named School of ECE Distinguished Professor at Georgia Tech in 2002, and awarded a special commendation from the Vice Provost for Research in recognition of his contributions to graduate-level education in 2002. In 2003, he received the highest honor that a Georgia Tech faculty member can attain: the Class of 1934 Distinguished Professor Award. He also served as an IEEE Electron Device Society Distinguished Lecturer.

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To my family, Lea, Casper, and Jack

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Preface

At the time of this writing the microelectronics industry is poised at the threshold of a major turning point. For nearly fifty years, the industry has grown from the initial invention of the integrated circuit through the continued refinement and miniaturization of silicon based transistors. Along with the development of complementary metal oxide semiconductor circuitry, miniaturization of semiconductor devices created what has been called the information revolution. Each new generation of devices leads to improved performance of memory and microprocessor chips at ever reduced cost, thus fueling the expansion and development of computing technology. The growth rate in integrated circuit technology, a doubling in chip complexity every eighteen months or so, is known as Moore's First Law. Interestingly, the semiconductor industry has been able to keep pace with Moore's First Law and at times exceed it over the past forty years. However, now at the beginning of the twenty-first century doubts are being raised as to just how much longer the industry can follow Moore's First Law. There are many difficult challenges that confront CMOS technology as device dimensions scale down below 0.1 μm. Many people have predicted that several of these challenges will be so difficult and expensive to overcome that continued growth in CMOS development will be threatened. Further improvement in device technology will then require a disruptive, revolutionary technology.

One might first wonder why is it important to continue to improve microprocessor speed and memory storage much beyond current levels? Part of the answer to this question comes from the simultaneous development of the telecommunications industry. Both lightwave communications and cellular communications systems have grown rapidly. Over just the past ten years, the cellular telephone industry has increased exponentially, making it one of the fastest growing industries in the world. The expansion of cellular telephony to the transmission of data, internet connections, and video information is already beginning. Cellular transmission of video information will require much higher bandwidth operation and greater sophistication than is currently available in cellular systems. Lightwave systems already handle video and internet communications and are pressed to improve bandwidth for faster operation. Though improvement in software and algorithms has been highly instrumental in improving telecommunications system capacity, hardware improvements are equally as important to maintain growth in these systems. Therefore, there is an acute need for faster electronics with a concurrent memory enhancement to improve telecommunications systems, thus further fueling the information revolution.

It is my opinion that the microelectronics industry will necessarily continue to grow to meet the demands of future computing and telecommunications systems.

However, this growth may not be confined to silicon CMOS but may extend into several other technologies as well. The goal of this book is to present an introductory discussion to undergraduate students of the basic workings of current semiconductor devices used in computing and telecommunications systems and to present some of the emerging revolutionary approaches that microelectronics could take in the near future. Throughout the book, the applications and operating requirements imposed on semiconductor hardware by computing and telecommunications applications are used to describe the important figures of merit of each device. In this way, the student can clearly see what fundamental properties a particular device must have to meet the system application requirements for which it is designed.

One might wonder why yet another book is needed on semiconductor devices for undergraduate education. This question is particularly relevant in that several universities have recently decided to abandon requiring an undergraduate course in semiconductor devices, making it solely an elective instead. Given that there are several excellent texts, such as Streetman and Banerjee *Solid State Electronic Devices* (2000) or Pierret *Semiconductor Device Fundamentals* (1996), one might wonder why another undergraduate book is needed especially in light of the fact that the need for undergraduate books is apparently decreasing. Though the above mentioned books are unquestionably excellent, they do not provide a discussion of the future of microelectronics and how it relates to the greatest existing growth industries of computing and telecommunications. It is the primary purpose of this book to provide the context, namely computing and telecommunications, in which semiconductor devices play their most important and ubiquitous role. Further, the present book provides a look at not only the state-of-the-art devices but also future approaches that go beyond current technology. In this way, a new, refreshing, up-to-date approach to teaching semiconductor devices and exciting the students about the future of the field is provided. It is my opinion that through an enlightened approach the negative trend of the removal of microelectronics courses from undergraduate curriculums can be reversed. Ironically, I believe that microelectronics is poised for its greatest surge. Thus rather than abandoning teaching microelectronics, it should be more widely presented and the approach should be more interdisciplinary at least addressing possibilities in molecular and biological systems for future computing hardware. This book presents a first cut at such an interdisciplinary approach.

This book has grown out of notes used for an undergraduate course I teach in the School of Electrical and Computer Engineering at Georgia Tech. The course is one semester long and follows a required course in circuit theory that includes some of the basics of semiconductor devices. However, the book does not draw on the student's knowledge of circuits and can thus be used as a first course in semiconductor devices. Given that the presentation is a bit briefer than most semiconductor device texts on the fundamentals, the book is probably better suited for either a second level course, as is done at Georgia Tech, or a first level course for more advanced students. As for scientific and mathematical background, the book requires knowledge of calculus and differential equations. However, no knowledge of quantum mechanics, solid state physics or statistical mechanics is required. Computer based assignments have not been included in the text. The main reasons for their exclusion is that we are preparing a computer based exercise book for use in all of our undergraduate level microelectronics courses. The proposed book will have computer exercises that follow the present book providing another path for learning.

The present book is organized as follows. It begins with a presentation of the essential fundamentals of semiconductors. The second chapter discusses carrier action. The third chapter focuses on junctions including p–n homojunctions, Schottky barriers, and ohmic contacts. In the fourth chapter, bipolar junction transistors are presented. JFETs and MESFETs are discussed in Chapter 5, including ac models. Chapter 6 presents a discussion of metal insulator semiconductor systems particularly MOS devices, long channel MOSFETs, and CMOS circuits. Short channel devices, scaling and challenges to further improvement of CMOS devices are discussed in Chapter 7. Chapter 8 presents a discussion of several different technical approaches that go beyond CMOS. The topics in Chapter 8 are limited to those that do not require knowledge of quantum mechanics. These topics are included in the graduate level textbook *Theory of Modern Electronic Semiconductor Devices* (2002) by Kevin F. Brennan and April S. Brown. The balance of the book focuses on device use in lightwave and cellular telecommunications systems. Chapter 9 gives an overview of telecommunications systems, both wired and wireless. In Chapter 10 a discussion of optoelectronic devices used in lightwave communications systems such as LEDs, lasers, erbium doped fiber amplifiers, semiconductor optical amplifiers and photodetectors is presented. The book concludes with a discussion of transistors used in high frequency, high power amplifiers such as MODFETs and HBTs in Chapter 11.

This book is designed to be the first in a series of texts written by the current author. It provides an introduction to semiconductor devices using only for the most part classical physics. Some limited discussion about spatial quantization is included, however. Thus the present book is well suited to the typical junior or senior level undergraduate student. After completing a course that utilizes the present book, the student is prepared for graduate level study. At Georgia Tech graduate students in microelectronics begin their study, following an undergraduate course at the level of the present book, with the basic science of quantum mechanics, statistical mechanics, and solid state physics covered in *The Physics of Semiconductors with Applications to Optoelectronic Devices* (1999), by Kevin F. Brennan. This material is covered in a first semester graduate level course that is followed by a second semester graduate level course on modern electronic devices. The textbook for the second semester graduate level course at Georgia Tech is *Theory of Modern Electronic Semiconductor Devices* (2002) by Kevin F. Brennan and April S. Brown.

Pedagogically, the undergraduate course this book has been developed from is taught three times a year at Georgia Tech. This course is a second level course in semiconductor devices that follows a required course that contains both circuit theory and elementary semiconductor material. Since the book is used at Georgia Tech for a second level course, we typically quickly cover the topics in Chapters 1–3 in about 2–3 weeks. Depending upon the student's preparation, the fourth chapter can be skipped, substituting a brief review instead. The course gets "down to business" beginning with

Chapter 5 and goes through the remaining chapters for the balance of the semester. Often we skip the section on CMOS (this is covered in the circuits level course) as well as Chapter 9 which is generally just assigned reading. Homework problems are typically selected from those at the back of the chapters. Two in-class quizzes and a final examination are given. Instructors can obtain a solutions manual for the problems on-line at www.ece.gatech.edu/research/labs/comp_elec. The solutions manual can be downloaded and is password protected. Instructors only are given access to the solutions. Please follow the directions at the web site to obtain the necessary password.

The author would like to thank his many colleagues and students at Georgia Tech that have provided constructive criticism in the writing of this book. Specifically, the author is thankful to Mike Weber for his help on some of the figures and for assisting in creating the book web site. Thanks go to Professor Wolfgang Porod of Notre Dame University and to Dr. Phaedron Avouris at IBM for granting permission to reproduce some of their work.

Finally, I would like to thank my family and friends for their enduring support and patience.

Postscript

Professor Kevin Brennan, my colleague at Georgia Tech, and one of my best friends, passed away on August 2, 2003. After he became ill, he continued to work on this text during the last year of his life, and had essentially completed it at the time of his death. I became involved at the copy-editing stage, and would like to express my appreciation to his wife, Lea McLees, for allowing me to assist in bringing this text to conclusion. I would like to acknowledge the effort of Ms. Maureen Storey, whose meticulous attention to detail was essential to the completion of the project. Most of my corrections and additions were reactive to her questions and comments. Eric Willner at Cambridge University Press showed considerable patience in both coaxing us and allowing us time to polish the text. The Chair of the School of Electrical and Computer Engineering at Georgia Tech, Dr. Roger Webb, provided both emotional and tangible support during this difficult period. Professor Christiana Honsberg and Professor Tom Gaylord at Georgia Tech provided answers to questions from me at critical junctures. Kevin Brennan was a superb teacher, accomplished researcher, and prolific author. I am appreciative of the fact that he is able to teach us one last time.

Atlanta, GA
March, 2004

W. Russell Callen

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Kevin F. Brennan
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More information

Physical constants

Avogadro's constant	N_{AVO}	6.022×10^{23}	Mol^{-1}
Boltzmann's constant	k_B	1.38×10^{-23}	J/K
		8.62×10^{-5}	eV/K
Electron charge	q	1.6×10^{-19}	C
Electron rest mass	m_0	0.511×10^{6}	eV/C^2
		9.11×10^{-31}	kg
Permeability – free space	μ_0	1.2566×10^{-8}	H/cm
Permittivity – free space	ε_0	8.85×10^{-14}	F/cm
Planck's constant	h	4.14×10^{-15}	eV s
		6.63×10^{-34}	J s
Reduced Planck's constant	$\hbar$	6.58×10^{-16}	eV s
		1.055×10^{-34}	J s
Speed of light	c	3.0×10^{10}	cm/s
Thermal voltage – 0300 K	$k_B T/q$	0.0259	V

Material parameters for important semiconductors, Si and GaAs

Bulk material parameters for silicon

Lattice constant (Å)	$a = 5.43$
Dielectric constant	11.9
Intrinsic carrier concentration (cm^{-3})	1.0×10^{10}
Energy band gap (eV)	1.12
Sound velocity (cm/s)	9.04×10^5
Density (g cm^{-3})	2.33
Effective mass along X (m^*/m_0) – transverse	0.19
Effective mass along X (m^*/m_0) – longitudinal	0.916
Effective mass along L (m^*/m_0) – transverse	0.12
Effective mass along L (m^*/m_0) – longitudinal	1.59
Heavy hole mass (m^*/m_0)	0.537
Electron mobility at 300 K (cm^2/(V s))	1450
Hole mobility at 300 K (cm^2/(V s))	500
Thermal conductivity at 300 K (W/(cm °C))	1.5
Effective density of states in conduction band (cm^{-3})	2.8×10^{19}
Effective density of states in valence band (cm^{-3})	1.04×10^{19}
Nonparabolicity along X (eV^{-1})	0.5
Intravalley acoustic deformation potential (eV)	9.5
Optical phonon energy at Γ (eV)	0.062
Intervalley separation energy, X–L (eV)	1.17

Bulk material parameters for GaAs

Lattice constant (Å)	$a = 5.65$
Low frequency dielectric constant	12.90
High frequency dielectric constant	10.92
Energy band gap at 300 K (eV)	1.425
Intrinsic carrier concentration (cm^{-3})	2.1×10^6
Electron mobility at 300 K (cm^2/(V s))	8500
Hole mobility at 300 K (cm^2/(V s))	400
Longitudinal sound velocity (cm/s) along (100) direction	4.73×10^5
Density (g/cm^3)	5.36

Effective mass at Γ (m^*/m_0)	0.067
Effective mass along L (m^*/m_0)	0.56
Effective mass along X (m^*/m_0)	0.85
Heavy hole mass (m^*/m_0)	0.62
Effective density of states conduction band (cm^{-3})	4.7×10^{17}
Effective density of states valence band (cm^{-3})	7.0×10^{18}
Thermal conductivity at 300 K (W/(cm °C))	0.46
Nonparabolicity at Γ (eV^{-1})	0.690
Intravalley acoustic deformation potential (eV)	8.0
Optical phonon energy at Γ (eV)	0.035
Intervalley separation energy, Γ–L (eV)	0.284
Intervalley separation energy, Γ–X (eV)	0.476

Note: Γ designates a point in k-space; X and L designate directions in k-space. Γ refers to the $k = 0$ point at the center of the Brillouin zone. X refers to the {100} directions and L to the {111} directions.