

Preface

History and Motivation

Teaching of transistor electronics began at the graduate level when John Bardeen offered the famous joint-departmental course EE-Physics 435, *Conduction of Electricity in Solids*, at the University of Illinois at Urbana-Champaign in the spring of 1952, which this author audited in 1953 as a senior. Shockley's book [199.1] was used as the textbook. Karl R. Spangenberg started a senior-graduate course on electron devices consisting of both vacuum tubes and transistors at Stanford in 1954 using his book, *Fundamentals of Electron Devices*, which this author served as the reader. After joining Stanford faculty from Bell Telephone Laboratories in 1955, John G. Linvill started a graduate course on transistor circuits using his book with James F. Gibbons, *Transistors and Active Circuits*. It took more than a decade for transistor device and circuit to be taught to undergraduate electrical engineering students. It began when the **Semiconductor Education Committee (SEEC)** was formed with a grant from the Ford Foundation in the autumn of 1960 to develop teaching materials by bringing together 18 professors and 13 industrial engineers with MIT Professors Campbell L. Searle as the Chairman and Richard B. Adler as the Technical Director, using students from MIT and elsewhere to test the materials. A textbook series of seven volumes was published in 1964 [750.1]-[750.7] covering materials physics, device physics-theory-model, and analog-digital circuits. Only bipolar junction transistor is described. In addition to being used worldwide, this series served as the basis for subsequent introductory junior level device and circuit textbooks written by several SEEC professors in the next five years, such as *Semiconductor Electronics* (1962-1964) by James F. Gibbons of Stanford; *Introduction to Electronic Systems, Circuits, and Devices* (1964-1966) by Donald O. Pederson, Jack J. Studer, and John R. Whinnery of Berkeley; *Electronic Principles, Physics, Models, and Circuits* (1969) by Paul E. Gray and Campbell L. Searle of MIT. These ten books, all focused on bipolar junction transistors, set the bench mark on the quality and depth of understanding of the **fundamentals** of semiconductor devices by undergraduate students during the 1960's decade.

Beginning in the early 1970's, additional introductory textbooks were written by third generation young teachers to include new semiconductor devices, such as the field-effect transistors, light-emitting diodes, junction lasers, photodiodes, solar cells, and photo-transistors. However, the quality and depth of fundamentals have not been maintained at the level of the SEEC volumes. The leading electrical engineering departments (such as MIT) then adopted a hybrid approach in textbook selection for the device core-course by supplementing the new and old junior texts with as many as a dozen intermediate and advanced books and monographs on devices and technology written by industrial engineers such as the compendious *Physics of Semiconductor Devices* by S.M.Sze and the epitomic *Physics and Technology of Semiconductor Devices* by A.S.Grove. But most EE departments (such as Illinois) used the new books alone, resulting in more than two decades (1970-1990) of American undergraduate electrical engineers who were educated at best as designers and technicians, if not pedestrians,

versed only on using recipes, rather than also innovative engineers and scientists. The inadequate fundamental education weakened their ability to compete with foreign students in graduate schools and foreign manufacturers in the marketplace on high-performance, low-cost products.

The need for a new introductory junior textbook in solid-state electronics to include new devices, still versed on fundamentals that equal or exceed the SEEC series, has been consensually recognized by solid-state electronics teachers in the last decade.

This book was conceived in the fall of 1980 when I was asked by Edward W. Ernst, then associate department head at Urbana, to teach the introductory junior core course in semiconductor devices. The first two volumes of the MIT SEEC series were selected and supplemented by about 100 pages of my own notes on materials physics and MOS transistors. The exceptional quality of this class of students (20 out of 25 had >4.5/5.0 grade-point-average) and the fundamental depth of Illinois' freshman chemistry and sophomore general and modern physics courses helped the success in teaching what I considered a necessary set of fundamentals which all electrical engineering undergraduates should comprehend. This experiment provided the initial encouragement that the situation is not hopeless for any instructor who is willing to spend the time to refresh, relearn or update his or her background knowledge in freshman chemistry and sophomore physics, if an up-to-date textbook on solid-state electronics containing materials physics, device physics, device theory, and basic circuits is available.

The growth of this book began unexpectedly at Florida in January 1989 when I was asked by colleagues to suggest a suitable textbook for the autumn and spring offerings of the core course on semiconductor devices in electrical engineering. I responded that I will update my 1980 lecture notes and also give the lectures because it was not clear how the material could be taught. Thus, several future lecturers also attended.

To cover the material in one semester efficiently and effectively, the latest teaching aids as follows were used instead of the traditional chalk and blackboard. In the three months prior to the fall semester, the 100 pages were expanded to about 500 typewritten pages using a personal MicroVAX-2 home computer and the MASS-11 scientific word processor. The 500-page text was distributed in seven chapters (see chapter list following this preface) to the 60 registered students about one week before the start of each chapter so that students could read the material before the lecture.

Viewgraphs were used instead of blackboard. Xerox copies of the viewgraphs (totaling 200 for the whole semester) were prepared before each lecture and distributed to every student at the start of the lecture so that the students could concentrate on the lecture without diversion from having to copy down the materials from the blackboard.

The lectures and viewgraphs followed the text with minimum deviation so that students could review at home what was not heard or remembered during lectures. The lectures emphasized the fundamentals: such as the technique of understanding and

Preface - History and Motivation

deciphering a materials or device phenomenon, via back-of-the-envelope calculations when desirable, using a set of fundamental laws and concepts already learned in freshman chemistry and sophomore physics, (Newton, Coulomb, Planck, de Broglie), and the derived relationships or concepts (electron-pair bonds, energy levels, Boltzmann, Fermi); rather than the traditional method of teaching circuit analysis via intensive numerical drills that aim for problem solving speed with little or no attention paid to the physical significance (or physics) of the numerical as well as the analytical results with the consequence that they are just random numbers from busy work and quickly forgotten.

Derivations of the atomic and crystal models and electron conduction in the crystals from the basic laws, the diode equations from diffusion and generation-recombination equations, and the transistor equations from the diode equations were presented as work-out examples, which are also given in the text. They were supplemented in the lecture by physically illustrative and engineering-significant numerical results as additional work-out examples. The physical significance of the numerical results were emphasized in order to be remembered for later use to estimate device effects, such as: how many electrons in a unit cell, in a cubic micron of the base layer of a 100GHz BJT, or in submicron size conduction channel of the $0.5\mu\text{m}$ MOS transistor in a 16Mbit DRAM, and what is the number fluctuation and limit on noise margin because of so few electrons.

Several innovations were introduced in my teaching of this course which caused initial anxieties not only in students but also colleagues, the latter soon became practitioners themselves. First, the students were given a table listing the page numbers of freshman chemistry and sophomore physics textbooks (Table 141.1) to review the basic laws and their experimental basis which were only briefly described in the lecture. This is consistent with the proven technique in teaching and learning: a language or a subject cannot be learned well and efficiently if prior learning is forgotten. New knowledge is built on previous knowledge, a well-known conviction of veteran authors and educators such as W.L.Everitt (lines 9-10, page v in *Communication Engineering*, 2nd edition 1937), F.E.Terman (lines 1-2, page vi in *Electronic and Radio Engineering*, 1955 and earlier, 1937, 1947 editions), A.P.T.Sah (lines 17-19, page viii in *Fundamentals of Alternating-Current Machines*, 1946 edition), and others; as well as inventors such as John Bardeen in every one of his public responses to the numerous inquiries and interviews by reporters on his path to the two Nobel prize winning contributions.

Second, the students are encouraged to learn as a team, but they must provide the homework solutions in their own words. They might just as well learn team work early because there are few if any silicon integrated circuit projects (for that matter, any modern engineering projects) that can be completed by one engineer: the success of a project depends strongly on the cooperation among the team members. Furthermore, the learning process is much more efficient and effective if the learners are prompted with regenerative feedback in a group or team. (For the latest success story, see *GE KEEPS THOSE IDEAS COMING* reported by Thomas A. Stewart in **FORTUNE**, 40-49, August 12, 1991, which exemplified the crucial reliance of the overall success of a company not only

on the interperson team but also its extension to interdepartmental team, inter-manufacture-supplier team, and ultimately, interproduct team.)

Third, all examinations are take-home and open-book! It is more important to test the students on fundamental understanding than their memorization ability and raw number-crunching speed. What engineering development or improvement project today depends on the memory of one engineer? Besides, we must have more confidence in the integrity and honesty of our youths. Electrical engineering undergraduates are usually the cream of the crop and serious students. They are not likely to be just degree and grade seekers to get high-paying jobs. They want to learn the basics and the fundamentals which will propel them in their entire professional life.

Nonetheless, it is the duty of the instructor to lead the students by showing the connection between what was learned and what is to be learned. The scant effort of making this connection to freshman chemistry and sophomore physics is prevalent in American electrical engineering education if not all engineering education as evident from the preface and contents of most of the introductory and advanced textbooks in physical electronics of the past three decades. It is this lack of 'building on previous knowledge', or even worse, rejecting the previous fundamental knowledge as practiced by some graduate thesis advisors and undergraduate instructors, that have severely degraded the quality of American electrical engineering education to empiricism and "recipeism" from engineering science. It is a vicious circle: younger (and some older) professors had not and could not have learned well from his or her former professors who had not reviewed and relearned the fundamentals. Thus, the current professors in electronics must start to relearn their freshman chemistry and sophomore physics so that we can get out of this vicious circle of continuously decreasing quality of fundamental knowledge in electronics and other physics- or chemistry-based engineering sciences.

The book then doubled to 1000 pages when I decided to add the intermediate-advanced materials to each chapter for several reasons which I shall give to respond to the protest 'The book is so heavy ... (but not proportionally expensive, thanks to World Scientific)': (1) to allow the reader to go directly to a graduate textbook on devices and materials physics, and to research and engineering literature; (2) to serve as a bridge to the next level circuit courses by introducing the basic-building-block circuits (1-transistor RC amplifier, 1-transistor memory cell, 2-transistor inverters, 2-transistor memory cells, etc.) normally taken up in the first part of the next transistor and integrated circuit course; and (3) to provide enough material for a second-semester device course. Objective (3) is incomplete because of the author's time limitation for this project. Thus, chapter 8 is absent which describes the principles of optoelectronic or light detecting and generating devices which contains photoconductive, photovoltaic, photoelectric, and light emitting and imaging devices. It is a planned addition for the second edition.

The key advantage of including these intermediate-advanced materials in one volume lies in its continuity of presentation, consistency of symbols and terms, and uniformity of basic physics. From the author's 25-year experience at Urbana in

Preface - Organization

developing the materials for an advanced graduate course in semiconductor and solid-state physics, and in theoretical semiconductor physics research with his physics doctoral students, it is possible to present the introductory and intermediate-advanced materials on the same fundamental physics bases and employ the same mathematical techniques as those used by the advanced graduate courses, but at a level understandable to the junior students using their prior freshman chemistry and sophomore physics backgrounds. Thus, models traditionally used as idealized elementary examples, in introductory books of physical electronics, transistors, and even solid-state physics, that require pages of algebra are rejected (for example, the box model to compute the electronic density of state, the Krönig-Penney periodic potential which would have been a good example if it were Fourier-analyzed rather than exactly solved, the latter results in obscurities that eclipse the fundamentals, etc.). They are discarded not only for their algebraic complexity (results cannot be remembered by the students and probably not even by the professors) but also for their erroneous impression of a real crystal. Instead, the one-dimensional results of the real solid, using elementary mathematics and physics, are presented at a level easily understood by a junior student with background in freshman chemistry, sophomore physics, calculus, and some elementary differential equations (for example, the periodic boundary condition, the simple Fourier expansion, the tight-binding atomic orbital expansion, the Bloch theorem with its analogy to AM radio waves, etc.). Thus, the starting points used in this introductory book for junior students are exactly the same as those used by the advanced graduate solid-state and semiconductor physics courses and by the research and engineering literature. In consequence, this approach has a singularly important pedagogical advantage over the traditional approach: the students do not need to unlearn any erroneous concepts and tedious techniques which he or she was taught via the traditional route. In addition, the students are taught the most basic foundations rather than intermediate results (cause-effect or cause-consequence rather than effect-effect or consequence-consequence correlations) so that they can qualitatively understand and quantitatively solve any future new problems starting from the most fundamental laws and concepts of physics and electrical engineering, even attaining the back-of-the-envelope proficiency of famed physicists.

Organization

The book contains seven chapters which are listed on page xvi. The detailed section contents are given in the subsequent 10 pages, xvii to xxvi. The first three chapters provide the background on materials physics, with work-out examples which include solid-state/semiconductor applications of the basic laws. For example, the Bohr atom is described using the Coulomb and Planck laws, and its applications presented include: the one-dimensional energy level and two-dimensional orbital diagrams, and the transition-energy diagrams for electron-photon interaction; the electron-pair bond model from the 2-d electron distribution in a Bohr atom, and the bond concept of holes and electrons in a solid; the formation of the periodic potential in the interior of a crystal by bringing many Bohr atoms together, and the crystal's electron affinity at its surface or vacuum/solid interface, which also serves as an introduction to solid/solid interfaces such

as the p/n, metal/semiconductor, and metal/oxide/semiconductor interfaces. Other examples are: the concept of global and partial equilibrium and their everyday physical realities; the description of the electron drift and diffusion phenomena via a statistical extension to solids of the classical Newtonian solution of electron motion in the scatterless vacuum to give the measured transistor parameters which are time- and ensemble-averaged over random scattering events in the semiconductor; the manufacturing analogue of time and ensemble averages; and the fundamental creation and destruction mechanisms of electrons and holes in semiconductors via generation-recombination-trapping and tunneling based on the classical energy and momentum conservation or exchange laws.

The next four chapters then describe diodes and transistors. The following sequence is presented for each device: **history** (invention, motivation), **fabrication** (a fabrication process flow chart, process chemistry-physics and theory, and process kinetic data), **device** (theory, models: d.c., small-signal a.c., large-signal transient), **B³C** (basic-building-block circuits: small-signal, switching, logic, memory), **bibliography** (with comments and selection of chapters and sections), and **problems** (tied to section by section number). The mass-produced and widely used devices are selected. It starts with the MOS capacitor in chapter 4 because it is the simplest device to describe and analyze, and it is also the structure that has the highest appearance frequency in all semiconductor devices and integrated circuits, thus most likely to be encountered by a BSEE in the first job. The p/n, m/s (metal/semiconductor), and ohmic junctions are then described and analyzed next in chapter 5. The MOS field-effect-transistor (MOSFET) comes next in chapter 6, before the bipolar junction transistor (BJT) in chapter 7, because MOSFET has replaced BJT since 1980 in integrated circuits and applications (such as the PC, VCR, TV, stereo, automobile, other appliances, and also industrial electronics), and because MOSFET is conceptually and mathematically simpler than BJT. The seventh chapter on BJT is the longest (~300 pages) because the BJT theory has not been adequately and correctly treated entirely in existing text and reference books, and because of the importance of using BJT as the output driver to increase the speed of MOSFET such as in the BiCMOS and CBiCMOS inverter circuits, and finally because of the revival of an Si-VLSI-process-compatible picosecond BJT technology, due to a recent breakthrough at IBM on commensurate growth of Ge epitaxial film on Si substrate. It has given an Si/Ge_xSi_{1-x}/Si BJT, with smaller energy-gap in the base, that has approached 100GHz without even optimizing the transistor structure and Ge and dopant impurity profiles.

Pedagogy

Special care was taken in the selection of symbols and their superscripts and subscripts. The basic rules are: (1) **it must tell the physics at one glance**, whether new or already seen, (2) the number of characters in the superscript and the subscript is limited to two and separated by a hyphen or differentiated by a change of case if it exceeds two due to a sub-categorization, (3) the fundamental parameters are denoted by Greek letters (μ , τ) while the applied parameters (D_n , L_B) and circuit variables [$v_{BE}(t)$, V_{cb} , V_{EB} ...] are

denoted by English alphabets, and (4) the IEEE Standards on symbols and their subscripts and superscripts are adhered to.

Special care was also taken on the choice of terminology. The same rule for symbol selection is used: the term and acronym must tell the physics at one glance, whether the first or a later glance. Traditional usage is followed if feasible which is generally possible because most solid-state/semiconductor and transistor terms were coined by pioneer physicists (Bardeen, Shockley, Slater and the previous English and German physicists) who carefully thought through the choices based on physics during the selection process. Semantically erroneous buzz words that confuse the physics are avoided, for example, the frequent use of the term 'bandgap' for energy-gap alone, started at RCA in the mid-1970's but avoided by Bell Labs until recently (see 1991 IEEE Field Awards citation in the August issue of **SPECTRUM**), rather than for the antonymous pair, energy-band and energy-gap. A similar usage for the antonyms frequency pass-band and frequency stop-band of the ω - β diagram of two-port networks would have been the unwieldy and obscure 'pass-stop' for the frequency stop-band. Fortunately, there are not many misuses in the trade. The importance of using semantically correct scientific terms is stressed in evaluating students' homework and examination solutions.

Considerations were also given to the selection of a new format for numbering the sections. The traditional usage of multiple decimal points for denoting subsections and sub-subsections is rejected because it is both hard to pronounce clearly to be understood in a lecture and confusing to look at when more than one dot is used. (It does not meet the 'one-glance' and 'one-word' criteria.) After several trials, cxy became the final choice: c=chapter number, x=first-level or sub-category number, and y=second-level or sub-sub-category number; and x=0 and/or y=0 are exclusively used for the introduction paragraphs of chapters and subsections, including history and motivation. Equations are numbered by (123.4A), ... where 123 is the section number and 4A is the fourth equation (4B would have been the fifth equation closely related to the fourth). Figures are numbered by Fig.123.4(a),(b), Furthermore, the section and book title appear in the header of every page (including the content pages) to help the reader locate a specific subject or section and to help the students remember the book title which few of the even most avid students habitually do.

A 'based-on-prior-knowledge' logical flow diagram of this book is shown on the following page. The approximate coverage for a one-semester 3-credit introductory course consists of all but the advanced sections of chapters 1-3 to be given in 5 to 6 weeks in 15 to 18 lecture hours. The remaining time, 8 to 9 weeks or 24-27 lecture hours, covers chapters 4-7, including the history and fabrication, the beginning sections on the analysis of each device (d.c., a.c. and switching), and selected examples of B³C (basic-building-block circuits). An extensive bibliography (approximately 100 entries or 90 books due to duplicate citations) is given at the end of each chapter in sections n99 (n=1 to 7). Several are listed for historical reasons but all are selected for some uniqueness in contents to allow the student to advance to the next level via self-study and directly to the senior or graduate courses. A description is given of the relevant chapters or sections in

each listed book for further self-study. About 500 problems are given. They appear at the end of each chapter and are numbered to track each section (such as P136.5 is the fifth problem for section 136). Most of the problems are designed to extend the theory and fundamentals rather than to provide numerical drills, the latter can be easily made up by the instructor if needed for some reason. A few review problems are given to exercise the student's analytical derivation or numerical analysis skills, by using a different set of parameters than those given in the text (such as holes while that of electrons is given in the text). Some (very few) unrealistic problems are also included although they are a waste of students' learning time, but favorites of some textbook authors and instructors who lack hands-on practical experiences. They are included rather than rejected in order to call attention to their lack of practical reality and the underlying reasons.

<p>Freshman Chemistry, Sophomore General and Atomic Physics, and Differential Equations Students are responsible for reviewing their prior knowledge.</p>	→	<p>Semiconductor Materials Physics Chaps. 1,2,3 5-6 weeks Excluding advanced sections.</p>	→	<p>Device Characteristics and Models Chaps. 4,5,6,7 History Fabrication D.C. A.C. Switching</p>	→	<p>B³C Basic Building Block Circuits Chaps. 4,5,6,7 A.C. Switching *Inverter *Memory</p>
					→	<p>Next Advanced Courses in: Circuits Devices Materials Physics</p>

The entire development and derivation of the transistor device theory and circuit application in this book is based on **four fundamental laws** which the students have already learned in freshman chemistry and sophomore physics: **Newton's** mechanical force law, **Coulomb's** electrostatic force law, **Planck's** energy-frequency quantization condition, and **de Broglie's** momentum-wavelength postulate. Pauli's exclusion principle and electron's spin of 1/2 are applied in analyzing the statistical occupation of quantum states but only stated, without mathematics, as the cause of the additional energy level splitting in heavy atoms and crystals due to the relativistic spin-orbit force. The small magnetic or Lorentz force and Ampère law (derivable from Coulomb's law in moving coordinate system using special relativity) is not discussed and not necessary to understand all the low-frequency (up to waveguide frequency) device characteristics since magnetic devices are not described in this book. Heisenberg's uncertainty principle is used to demonstrate some phenomena qualitatively, such as the energy-band width. The mathematical level required in the derivation reaches up to only Fourier series expansion. Diagonalization of a 2x2 matrix and Laplace transform were worked out and not assumed as prior knowledge although they are likely being taught in courses taken concurrently by the students.

Epilogue

In short, the subject of solid-state electronics is easier, more systematic, and just as realistic if not more realistic, than those taught in: freshman chemistry (~100 elements, hundreds compounds, maybe 100 empirical laws to remember, compared with 1 element, Si, or 2 elements, GeSi or GaAs, plus about three or four impurity elements, and four fundamental laws); **sophomore general and atomic physics** (many more examples to explain the hundreds of experimental phenomena compared with only two transport phenomena, drift and diffusion, and about 12 to 15 fundamental electron-hole generation-recombination-trapping processes from the 4 energy and 3 momentum exchange mechanisms presented in a simple 4x3 table); and **sophomore differential equations** (many more theories and numerous examples than this book). The claims and complaints that the content of this book is too difficult and too advanced as the first course for the junior students by some professors and students can be summarily rejected: they need to review their **prior knowledge** in freshman chemistry and sophomore physics, which are more complex and difficult. Teaching this material (or any material) for the first time is hard work for anyone, including the author himself, as proven also by colleagues who have successfully taught this material, in spite that some are veteran researchers in bipolar transistors for two decades. But it is the duty of the professors to revive the quality of American electrical engineering education by teaching fundamentals rather than result-result or consequence-consequence recipe. It is also the responsibility of the American engineering department and college administrators to provide support to help teach the material successfully in this and all core courses, including: **graduate teaching assistants** who have already learned this material and used it in research (a practice in the 1950's), additional faculty release time for teaching the subject first-time or using a new book, and junior faculty members for small-size discussion or quiz sections, as well as laboratories. Frequently, only undergraduate teaching assistants are assigned due to budget limitations. They had just taken the course and had no experiences in research, application, or more advanced course which are crucial background to help teach the beginners.

The entire book (cover pages, index, five to ten revisions of various parts of the text, and the final camera-ready copy) was composed and typed by the author on a personal MicroVAX-2 (manufactured by the Digital Equipment Corporation) using the MASS-11 scientific word processor (manufactured by the Microsystem Engineering Corporation). The author also mechanically hand-drew all the figures except a few which were redrawn by the publisher to sharpen the coordinate grid lines. This hands-on effort provides the capability to include the latest materials and make corrections right before the camera-ready pages are sent to the printer. In spite of the many editorial revisions of various parts of this book, there are probably still typographical errors. Thus, I welcome comments and reports, from both instructors and students, not only on the contents, presentation, and learning and teaching experiences, but also on any remaining typographical errors.