Preface

Semiconductor devices are the building blocks of modern electronics. Initially the devices available were confined to point contact diodes, point contact transistors, PN junction diodes, junction transistors (or bipolar transistors), and field effect transistors (FETs). Early versions of these were able to work only at low frequencies and low power levels. These limitations were soon overcome and now there are devices working at frequencies up to microwave and optical frequencies. For selected applications, there are power semiconductor devices like the thyristors (or SCRs) which can handle power of the order of kilowatts. In parallel with these developments, came integrated circuits (linear and digital, including VLSIs and VHSICs). There is indeed a very large array of devices in use today and many new devices keep appearing from time to time. Most beginners find it extremely difficult to get a proper understanding of even simple devices and thus lose interest in the subject. Hence, something has to be done to introduce the subject in a way in which the student not only finds it easy to understand and extremely interesting, but also becomes eager to take many high level courses in this area and pursue a career in this fascinating field. Indian Institute of Technology(IIT) Madras, has for a long time, enjoyed the reputation of having made this subject extremely simple to understand and enjoyable to students. We hope to achieve the same results with a wider audience, at least in a small measure by bringing out a book on this subject, though we know only too well that it is difficult to communicate through a book what we achieve by personal contact within the classroom.

Aim of This Book

The aim of this book is to give a lucid quantitative exposition of the fundamental concepts of semiconductor devices. The book is written in a fashion that will not only remove the fear of devices from the minds of students but also inspires them to follow higher studies in this area and choose a career in the exciting field of devices and other related fields like VLSIs.

Inspiration

While teaching the courses on semiconductor devices at IIT Madras, we were encouraged by the response of the students and many of them expressed that a textbook dealing with fundamentals of

semiconductor devices the way it has been taught by us would be a source of motivation for the student and teacher community to understand and pursue this exciting area for higher studies and research. Therefore, we decided to write this book making use of our teaching and research experience in this field. As luck would have it, around the same time Tata McGraw-Hill Publishing Company approached us with a request to write a good fundamental book suitable for undergraduate students in this field. Here is the fruit of our effort in that direction.

Target Audience

The book is aimed principally as an introductory text at about the 4^{th} semester level of undergraduates specializing in Electronics Engineering. We have found it necessary to introduce such a course in the first semester for our own postgraduate students also. Thus, the book is useful for a first course on Devices at the postgraduate level also. Over a hundred illustrative examples are provided to help the students at both the undergraduate and graduate level. Several challenging problems are given at the end of chapters.

Organization

The material presented in the book is organized in three Parts consisting of fourteen chapters. Part I (comprising Chapters 1 and 2) gives a detailed qualitative treatment of Semiconductors, PN junctions and Transistors, taking care to see that the qualitative nature of the treatment does not make it scientifically incorrect. This qualitative study is a prerequisite for following intelligently the quantitative treatment of Part II (Chapters 3 to 13). If followed in this sequence, the only prerequisite expected of the students is the knowledge of high school physics and exposure to an elementary course on Differential Equations and Electrical Circuit theory.

The quantitative treatment of devices given in Part II is necessarily based on the 'Energy Band Model' of the solid. However, the introductory study of Part I is deliberately based on the 'Atomistic Model' of the solid, in which we start with the Valence Bond Structure of the semiconductor crystal and try to 'visualize' electron motion within the physical space of the crystal lattice. It has been our experience that the clear physical picture thus formed, serves as a strong 'framework' around which the sophisticated concepts of the rigorous quantitative theory can be easily built. This two-tier approach adopted in the book helps the student to proceed smoothly from less difficult to more difficult concepts and get a clear grasp of the fundamentals of the subject. There is thus a smooth flow of material in a logical step-by-step fashion, without the student ever getting frightened of volumes of unwieldy equations right in the beginning.

In Part II, Chapter 3 deals with the quantitative theory of semiconductors using the Energy Band Model, followed by detailed quantitative treatment of PN junctions and Bipolar Transistors in Chapters 4 and 5. The material in these two chapters is presented in such a way as to enable students to quickly visualize the minority carrier density distributions in these devices under various conditions of applied voltages. From these, students can arrive at the qualitative and quantitative performance of these devices with little effort, without having to make complicated calculations. At this juncture, students will have an intimate understanding of devices which will make the rest of the study really enjoyable and fruitful. We have thus tried to make the subject extremely simple in these two chapters and build the remaining chapters on this strong foundation.

Quantitative analysis of junction transition capacitance and breakdown mechanisms of PN junctions is described in Chapter 6. The foundation laid in the previous chapters makes this topic seem simple and straightforward.

PNPN structures, photo-diodes, photo-transistors, etc. are treated in a unified manner in Chapter 7, which will enable students to identify the common thread running through many apparently unrelated structures. This is a special feature of the book. This has helped kind interest of our students in the study of devices and motivated them to experiment with devices in the laboratory on their own and plunge deeper into devices.

Chapter 8 gives a comprehensive quantitative understanding of the ac properties of PN junctions and Transistors and analyzes the transistor cutoff frequencies, diffusion capacitances and PN junction admittances using ac continuity equation. This prepares students for the high-frequency equivalent circuits of transistors.

Chapter 9, High Frequency Analysis and High Frequency Equivalent Circuits, introduces students to a powerful method of analyzing high frequency properties and deriving high frequency equivalent circuits of devices using the concepts of 'Complex Lifetime' and 'Complex Stored Charge', without having to laboriously solve ac continuity equations. This being a book on the fundamentals of devices, we have refrained from trying to exhaust the possibilities of this approach to tackle all types of high frequency and transient properties of devices, lest the book become too unwieldy.

Chapter 10 gives a simplified approach to understanding the Metal Semiconductor Contacts, both ohmic and rectifying types, bringing out the difference in the I-V characteristics of Schottkey barrier diodes and PN junction diodes. This chapter also gives the analysis of MESFET and JFET and their equivalent circuits. The relevance of MESFET to the present day high speed logic circuits is also discussed to encourage the students' interest in this topic. The analysis provides the concept of threshold voltage of MESFETs and JFETs useful in circuit analysis with equations similar to the familiar MOSFET equations.

Chapter 11 provides both qualitative and quantitative understanding of MOS capacitors and MOSFETs. It also gives a clear understanding of the ac properties such as transconductance and cutoff frequency, in addition to concepts of threshold voltage and dc characteristics of the MOSFET. A simplified analysis of the subthreshold characteristics is also presented in this chapter. Topics such as short-channel effects, etc. which occasionally find a place in some introductory level books have been deliberately left out so as to avoid confusion and fear in the minds of students at the undergraduate level.

The focus in Chapter 12 is on the basic principles of device fabrication rather than giving detailed fabrication steps, so as to sustain the interest of students and make it simple to understand. The concepts of present day planar technology, BJT structures in integrated circuits, and the popular device isolation technique are presented. This chapter also covers the MOSFET device fabrication processes and device scaling principles for VLSI and ULSI technology. We have also included NMOS, PMOS and CMOS technology, the generic problem of latch up in CMOS circuits and the power dissipation calculations. The strategy we follow in offering the courses on devices to students is to make the fundamentals of devices simple, interesting and exciting to them so that all of them get interested in the subject and want to take a number of in-depth additional courses in the area of devices. We, therefore, follow up this first course with a number of elective courses such as (1) Selected topics in Semiconductor Devices, (2) Power Semiconductor Devices, (3) VLSI technology and VLSI Design, (4) Compound Semiconductors, etc. which are favourites with the students. Keeping this aspect in view, we have restricted the coverage to laying a good foundation to the fundamentals of technology in this chapter as well as on all topics throughout the book.

Up to Chapter 12, we have dealt with topics that we think are most important in this field. However, our exposition on devices is by no means complete and hence we have included a small chapter

(Chapter 13) on 'Some Miscellaneous Devices' dealing with Tunnel Diode, Drift Transistor dealing with doping gradation effects, Hetero junction transistors, Diac, Triac, etc. just to bring these devices to the notice of the students, without going into too many details.

Chapter 14 gives a brief exposure to BJT based amplifiers dealing with the different amplifier configurations, biasing techniques and maximum signal output conditions, etc. This is presented in Part III of the book.

Road Map for Various Target Courses

We have taught separate courses on 'Semiconductor Devices' and 'Electronic Circuits' at various levels for well over three decades. The present book on 'Fundamentals of Semiconductor Devices' has been formulated based on this experience and interaction with students. Part I of this book gives a detailed qualitative treatment of Semiconductor and serves the dual purpose of introducing (1) Transistor Circuits and (2) Semiconductor Devices to students as follows: While teaching 'Circuits', we use only the material contained in Part I as an introduction to diodes and transistors qualitatively and proceed with the detailed analysis of transistor circuits using the devices background given in Part I. Similarly, while teaching 'Devices', we do not start with the quantitative picture of Part II, because it will not give any 'physical visualization' of what goes on in devices. So we use the material of Part I, which is in terms of the '*Atomistic Model*' of devices and follow it with the quantitative description of Part II, which is based on the '*Energy Band Model*'.

In our experience, this approach of introducing the material of Part I in both the 'first course on circuits' as well as the 'first course on devices" has been a great success with students crediting both the courses, namely (1) Transistor Circuits and (2) Semiconductor Devices. The present book was planned in two parts based on the success achieved with this approach. By the time the students go through the course on 'Transistor Circuits', they become quite familiar with the qualitative aspects of devices as well as Transistor Circuits, and would have used diodes and transistors in the laboratory. Therefore, it would be desirable that a full-fledged course on the 'Fundamentals of Semiconductor Devices' is taught after they have gone through a first course on 'Transistor Circuits' as mentioned above. On the background thus built up, it will be easier to build various higher level courses on Circuits as well as Devices and, thus, impart proficiency to students of both these disciplines.

We find that in some books on Devices, circuit applications of the particular device discussed in a chapter are also included in the same chapter along with device theory. In our opinion, it is better to have a separate book on circuits dealing with all aspects of different circuits, rather than include them in a sketchy fashion in a book dealing with Devices. Such a book cannot do justice either to Devices or to Circuits and can interrupt the smooth flow of the material. Thus, with the idea of avoiding mixing up of these two disciplines, we have not discussed Circuits in this book. We have introduced Part III in this book where bipolar junction transistor circuits are briefly included for the benefit of the students who have not yet had a course on this topic to familiarize them with this important area.

The book is written in such a way that Chapters 4 to 9, 13and 14 can be skipped by those who want to study mainly the basics of FETs and straight away go to Chapters 10 and 11 after studying the basics of semiconductors and junctions from the initial three chapters. On the other hand, those interested in bipolar devices can focus on Chapters 5 to 9 after studying the first four chapters.

In our opinion, after covering some courses on Mathematics, Physics and Electrical Circuit Theory in the first two semesters, a course on Transistor Circuits can be introduced in Semester 3, using Part I of this book as an introduction to the course. This can be followed by a formal course on Devices in Semester 4, using the material in Part II of the book (a rapid revision of Part I can serve as an introduction to this course too).

Salient Features

- First part of the book, presented in two chapters is dedicated for qualitative treatment of semiconductors, junctions and transistors to give a physical feel and understanding of the subject
- Exclusive treatment of high frequency analysis and high frequency equivalent circuit of transistors has been included as a full chapter.
- A generalized novel approach of 'Complex life time' and 'Complex stored charge' has been introduced to analyze the input impedance and output admittances of devices of complex structures.
- Special attention is given to the photodiode, phototransistor and PNPN devices.
- Metal semiconductor contacts are discussed in great detail leading to the analysis of MESFETs and MIS tunnel diodes and solar cells.
- MOSFET models (SPICE Level-1, 2 and 3) and Ebers Moll model for BJTs have been presented to make it useful to circuit engineers.
- A separate chapter dedicated to simple amplifier circuits and biasing technique is presented as Part III of the book.
- Over hundred worked examples have been provided spread over the book to illustrate the topics discussed in the text.
- Challenging homework problems are given at the end of each chapter.

Web Supplement/CD

The accompanying Web supplement http://www.mhhe.com/achuthan/fst gives

(1) teaching aids such as PowerPoint presentations for easy teaching
(2) solution manual for all the problems given at the end of the chapters, and
(3) model question papers. Additional features are being incorporated and will be updated from time to time.

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Reviewers

The book has been carefully reviewed by experts in this field and has been commended by them for its original approach to the subject matter. We would like to thank the following reviewers.

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The manuscript has been revised as per their suggestions. Also the publisher's suggestion to include several topics found in the syllabus of the various universities in the country has also been taken care of.

Feedback

We hope the book serves the purpose for which it has been written, namely, to be of use for practicing teachers and students interested in learning the Fundamentals of the Semiconductor Devices. Feedback, both from teachers and students, in the form of suggestions, criticisms and appreciation are most welcome. They can be sent either to Prof. M.K.Achuthan at mkapkm@vsnl.com or to Prof K.N.Bhat at knbhat@gmail.com or posted directly to the Web site.

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