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Fundamentals of SEMICONDUCTOR DEVICES

About the Authors

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During his teaching career of 39 years, nearly 30 years were spent at IIT Madras where he initiated teaching and research activities in the fields of Solid State Devices and Circuits and VLSI Design. A large number of his students are working in the fields of Devices and Circuits in industries and universities across the word.

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Contents

PART II QUANTITATIVE THEORY OF SEMICONDUCTORS, P–N JUNCTIONS, TRANSISTORS (BJTs AND FETs) AND TECHNOLOGY

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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We are deeply indebted to Professor V. Balakrishnan, Professor of Theoretical Physics, IIT Madras for having taken the pains to go through the material in Appendix A critically, and in great detail, and given us many valuable suggestions.

Our thanks are due to the several hundreds of our students who have displayed great interest in this subject during their study at IIT Madras. Their enthusiasm and appreciation of the way we taught this course have indeed motivated us to put things together in the form of this book.

We thank Mr. Thilakar Gandhi of the Department of Electrical Engineering for having spent days and nights for a long period, meticulously and painstakingly typing and re-typing and keying in almost the entire manuscript. Thanks are also due to Mr. D. Jayaseelan who rendered help during the initial part of the preparation of the manuscript.

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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.

1. M J S Rangachar, Crescent Engineering College, Vendalur, Chennai.
2. Ghanshyam Singh, MNIT, Jaipur.
3. R. B. Lohani, Government Engineering College, Goa.

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.

M K Achuthan
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PART I

Qualitative Theory of Semiconductors, P-N Junctions and P-N Junction Transistors

CHAPTER 1

Qualitative Semiconductor Theory

1.1 INTRODUCTION

The search for a rugged solid state element to replace the fragile vacuum tube triode as the amplifying device in electronics, and the effort mounted during the second world war and immediately thereafter towards the development of a reliable crystal detector for Radar to work at microwave frequencies, have together brought-in the new field of transistor electronics. Subsequent developments in this field have resulted in the birth of a very wide range of discrete semiconductor devices working over a wide spectrum of frequencies including the microwave and the optical region, and over a wide range of voltages, currents and power. Developments taking place in transistor electronics along totally different lines led to the advent of Integrated Circuits (ICs), whereby electronic circuits involving a large number of transistors as well as passive circuit components and interconnecting wires were built on a small semiconductor chip at one stroke.

Levels of integration achieved in the initial stages of IC development were quite moderate, resulting in Small Scale and Medium Scale Integrated Circuits—SSIs and MSIs. Then came Large Scale and Very Large Scale Integrated Circuits—LSIs and VLSIs—which pack-in several hundred thousand devices on a very small semiconductor chip of area less than one square centimeter. This made it possible to have very powerful chips for communication, signal processing, computation, storage, etc. and machines of such unbelievably large processing power as supercomputers which process several thousand million instructions per second.

The whole subject of semiconductor devices is built around the P-N junction transistor or the bipolar transistor, which is also the most well-investigated among devices. This aspect is reflected in the sequencing of material covered in this book and the importance given in this book to the intensive study of this device. All other devices are, therefore, built around this device in the book.

The aim of this book is to give a lucid quantitative exposition of the fundamentals of semiconductor devices starting from the scratch. The actual quantitative study is covered in Part II of the book. Part I gives a detailed qualitative treatment of semiconductors, P-N junctions and transistors. This qualitative study is a prerequisite for following intelligently the quantitative treatment of Part II. If followed in this sequence, there is no other prerequisite expected of the student, except a knowledge of high school physics and exposure to an elementary course on differential equations and circuit theory.

The quantitative treatment of devices given in Part II is 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. The clear physical picture thus formed serves as a strong "framework" around which the sophisticated concepts of the rigorous 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 gives a clear grasp of the fundamentals of the subject. This would require that the elementary theory given in this and the next chapter, does not involve any sacrifice of scientific accuracy for the sake of simplicity of treatment. Great care has been taken to ensure this.

It is one of the triumphs of modern physics that it has made it possible to trace all types of macroscopic behaviour of materials—e.g. the different mechanical, electrical, thermal, magnetic, optical and various other physical and chemical properties of different materials—to the microscopic behaviour of electrons around atoms. The laws which govern the dynamics of an electron in the electric field around atoms are quantum mechanical laws, which include Schröedinger's Equation, de Broglie Relations, Heisenberg's Principle, Pauli's Exclusion Principle, etc. Since the mathematics involved in their solution is extremely complex, rigorous solutions have been possible only for certain simple cases such as a hydrogen atom, a helium atom and a hydrogen molecule. Analysis of electron motion around other atoms and molecules involves the use of various types of approximations in the mathematical steps. However, in spite of all the approximations involved, wherever it has been possible to apply quantum mechanical equations in this manner, the theoretical predictions so made seem to agree very closely with experimental observations, whereas classical mechanics fails to predict correct results. Encouraged by this success, the theoretical physicists have boldly ventured to attempt to get solutions of these equations for electron motion in the complex electric field structure existing in a solid. In fact, the electric field pattern involved here is so complicated that it has been impossible to obtain solutions for equations such as Schrödinger's Equation for the motion of an electron inside a solid, without making several drastic approximations. We are not concerned here with the details of the methods used for such solutions by theoretical physicists but only in the final results of their work and applications of these results.

As a result of all the drastic approximations employed, theoretical physicists have brought forth two important "models" of the solid to analyse its behaviour, namely the "*atomistic model*" and the "*energy band model*". The approximations involved in one model are different from those involved in the other. Therefore, each model is quantitatively valid only for certain limited categories of the properties of the solid, consistent with the particular approximations employed. But within the limits of their validity, these models help to predict the results remarkably correctly. Thus, the atomistic model gives quantitatively correct results for properties such as those of mechanical cohesion, ferromagnetic behaviour, etc. but fails to do so for electrical conduction in solids. However, this model can give a qualitative understanding of certain electrical properties. On the other hand, the energy band model gives quantitatively correct results for the electrical properties of the solid, but not for many of the non-electrical properties. Therefore, in our quantitative study of semiconductors and semiconductor devices in Part II, we will have to use the Energy Band Model. In using this model to study the electron behaviour in a solid under the action of an externally applied electric field, we will not be ordinarily considering how an electron moves from one point to another in the physical space within the solid; but only how the electron energy changes under the action of the applied force field or how the electron moves from one quantum state at one energy to another quantum state at another energy in the abstract "k-space"† within a Brillouin Zone [17, 18], without reference to

† k is called the "wave vector", and is one way of defining a particular quantum state; $k = 2\pi/\lambda$ where λ is the wavelength defining the particular mode of motion or quantum state .

physical space. Few students who are beginners can appreciate this type of approach. Such a procedure does not give any physical feel to a beginner who is unfamiliar with the abstract concepts of "wave functions", "wave vectors" and "Brillouin Zones".

In view of the above difficulty faced by a beginner, the preliminary study of Part I is based on the atomistic model of the solid. Also, while using this model to study the effect of the superposition of an electric field on the solid and consequent electron motion, we will use classical physics as far as possible. Due to this, some of the final results may go wrong by a small factor. In such cases, the correct results obtainable from quantum mechanical considerations will be simply stated without proof. Rigorous procedures based on the Energy Band Model will be taken up in Part II.

1.2 SEARCH FOR A SOLID STATE AMPLIFIER

The action of an amplifier involves controlling the power released from a power source into a load. In the triode tube amplifier which was used for a long time at the early stages of electronics, the power source used was a battery or a d.c. supply and the control was done by varying the electron flow in vacuum from the cathode to the anode of the tube by means of a voltage signal impressed upon the control grid (see Fig.1.1 (a)). However, from a purely electrical circuit point of view, the triode tube is nothing but a variable resistance. And this variable resistance, namely the anode to cathode resistance of the tube, was varied by means of the voltage signal applied to the control grid. The variable resistance is realised here in an evacuated region which is made conducting by thermionic emission from the cathode.

Scientists toying with the idea of replacing this delicate device with a more rugged one in order to realise a solid state amplifier, thought of various ways of varying the resistance of a rugged piece of a conducting solid (shown in principle in Fig. 1.1 (b)). The resistance, R, of a piece of regular-shaped solid depends upon its length, ℓ, area of cross section, A, and the material resistivity, ρ, according to the relation,

$$R = \frac{\rho \ell}{A} \tag{1.1}$$

Any one of the three quantities, ρ, ℓ or A will have to be varied to vary R. It was not easily conceivable how the area of cross-section, A, of a piece of solid or its length, ℓ, could be varied electrically[†]. Therefore, the main attempt was to find ways of varying the conducting property of the material itself, viz. its conductivity, σ, or its resistivity, ρ, by means of an electrical signal.

Copper or other conductors were not found quite suitable for obtaining this variable resistance action. This is because it is not easy to devise a method of varying the resistance of a piece of conductor directly by means of an electrical signal. Therefore, one had to depend upon some intermediary such as heat to convert the electrical signal into a thermal signal and use the resultant temperature changes to bring about resistivity changes. Also, the thermal lag implied in this process became prohibitively large because of the large thermal capacities involved. This severely limited the frequency range over which the device could

[†]1. It may however be noted that in the present day Junction Field Effect Transistor (JFET) the input signal varies the resistance between the main electrodes (source and drain) by varying the effective electrical cross-sectional area of the conducting channel. Similarly, at a future date, it may also become possible to vary the effective electrical length of the conducting path of some suitable medium so as to vary its resistance.

2. Instead of a variable resistance, a variable reactance (either inductive or capacitive reactance) could also form the basis of an amplifier such as given in Fig. 1.1(b). In this case, the power source will have to be an a.c. source of suitable frequency. Some method of varying the effective permeability of the magnetic core of an inductance, or the effective dielectric constant of the dielectric of a capacitor, may be the means to achieve this end. In fact, some existing devices such as the magnetic amplifier, the dielectric amplifier and the parametric amplifier, work on this principle.

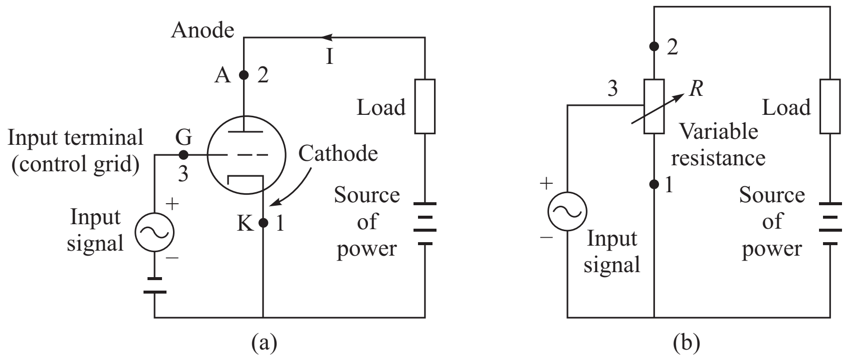

Fig. 1.1 *(a) Vacuum tube amplifier where the resistance between the anode and the cathode is being varied by the signal to have control over the release of power from a power source into the load. (b) Similar variable resistance action envisaged in a solid to effect control over the power released from the power source.*

work. Secondly, if a conductor were to form the variable-*R* in the amplifier setup of Fig. 1.1(b), the resultant percentage variation of the overall circuit resistance and hence the extent of control over the load current, were found to be negligibly small due to the small resistivity of these materials. Due to the above reasons, conductors were practically ruled out. This led to the trial of an insulator as the variable *R*. However, a method of varying the resistance of a piece of insulating material directly by means of an electrical signal does not appear to have been obtained so far.

Possibly due to these reasons, people working in this direction, seem to have concentrated mostly on a different class of materials known as semiconductors, where the resistivity is not as low as for conductors or as high as for insulators, but somewhere in between. The chances of one succeeding with these materials appeared to be better. In fact, when realisation of a practical solid state amplifier finally came about for the first time with the discovery of transistor action, it was achieved in one of the semiconductors, viz. germanium. Along with germanium, silicon also came up as a material for fabrication of transistors and other semiconductor devices. Germanium reigned supreme for a few years, to be replaced eventually by silicon, which is technologically the most dominant material today. Many other semiconductors, many of them naturally-occurring oxides and sulfides of many metals, were existent before the discovery of transistor action. Many newly developed inter-metallic compounds (such as gallium arsenide, indium antimonide, etc.) are also currently used for semiconductor devices. However, our present discussion will be confined to germanium and silicon.

Before trying to understand how the resistance of a piece of germanium or silicon can be varied by means of an electrical signal, it will be necessary to understand how resistance to current flow arises in these semiconductors or how application of a voltage gives rise to a finite current flow. Therefore, a good part of our initial study of transistors will have to be devoted to understanding the mechanism of current flow in solids in general and in germanium and silicon in particular.

1.3 CURRENT CARRIERS IN SEMICONDUCTORS

In early days, electric current was attributed to the flow of a positive charge from the positive terminal of the battery to the negative terminal through the external conductor. This idea changed with the evolution of