Electronic Devices and Circuits

third edition

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Preface

This book is intended for use in electronics technology courses in colleges and universities. It is also intended to be useful as a reference text for practicing electronics technicians, technologists, and engineers.

The text has been almost entirely rewritten for the third edition to update and expand the coverage taking into account suggestions from those who used the second edition. Some material has been condensed to make room for detailed treatment of more important subjects.

The objectives are to provide a clear explanation of the operation of all important electronic devices in general use today, and to impart a knowledge of electronic circuits using these devices. I am convinced that a thorough understanding of circuits is most easily achieved by learning how to design circuits. In general, circuit design is quite simple—much simpler than some methods of circuit analysis. After discussing device operation, characteristics, and parameters, the operation of a circuit is explained; then circuit design and analysis are treated. Many practical design and analysis examples are included in the text, using (maximum and minimum) device parameters derived from manufacturers' data sheets. Charts and nanograms are avoided, and most equations are derived so that the student knows exactly what is going on at all times. Instead of rigorous analysis methods, practical approximations are employed whenever possible.

Another objective, new to this edition, is to show how computers may be employed in circuit design and analysis. This subject is covered in the final chapter of the book, where examples of computer programs are given in both BASIC and PASCAL languages.

The topics in the book are arranged in a sequence that permits each subject to build upon earlier studies. Assuming that the reader is already familiar with basic electricity, the text commences with semiconductor and *pn*-junction theory, which is essential for an understanding of all solid state devices. Semiconductor diodes and diode applications are investigated next, followed by Bipolar Junction Transistor (BJT) operation. Transistor biasing and single-stage transistor circuits are then treated in detail, with many practical examples. Device and integrated circuit manufacturing methods are studied next, mainly from the point of view of device performance. Following this is a chapter on transistor specifications and transistor performance as related to the specifications, including power dissipation, frequency response, and switching times.

The operation of the Field Effect Transistor (FET) is explained in one chapter, followed by a chapter on FET biasing and another one on FET single-stage circuits. Once again, practical device parameters are employed in all circuit design and analysis examples.

With BJT and FET circuits understood, Chapter 11 covers small signal BJT, FET, and BIFET amplifiers. The design of each circuit is treated followed by circuit analysis. Negative feedback is studied in a very practical way in Chapter 12, by investigating negative feedback amplifiers.

Integrated circuit operational amplifiers are explained in Chapter 13, including op-amp applications and how to design IC op-amps into circuits. Since internally compensated operational amplifiers cannot always be used, Chapter 14 explains the problems of frequency compensation and shows how to select compensating components from manufacturers' data sheets.

Sinusoidal oscillators are the topic of Chapter 15 and, as always, design and analysis of practical circuits is explored. Examples are given of how to design for a specified output frequency and amplitude.

Because the most important application of the breakdown diode is as a voltage reference source, this device is introduced in Chapter 16, in which power supplies and voltage regulators are investigated. Coverage includes unregulated power supplies, discrete component regulators, op-amp regulators, and IC voltage regulators.

Chapter 17, on the subject of large signal amplifiers, includes transformer-coupled, capacitor-coupled, and direct-coupled circuits. Within the limits of available space, design of these circuits is explained and design examples are given.

Chapters 18 through 21 cover Thyristors and UJTs, Optoelectronic Devices, Miscellaneous Devices and Electron Tubes. Examples are again given of how to design each device into an appropriate circuit. Finally, as already mentioned, Chapter 22 enlists the computer in the study of electronic circuits.

Comments and suggestions from users of the book are welcome.

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1

Basic Semiconductor and *pn*-Junction Theory

Introduction

The function of an electronic device is to control the movement of electrons. The first step in the study of such devices is to achieve an understanding of the electron and how it is associated with the other components of the atom. The movement of electrons within a solid is next investigated, and the bonding forces between atoms are studied. This leads to a knowledge of the differences between conductors, insulators, and semiconductors, and to an understanding of *p*-type and *n*-type semiconductor material.

The *pn*-junction is basic to all but a very few semiconductor devices. Forces act upon electrons that are adjacent to a *pn*-junction, and these forces are altered by the presence of an external bias voltage. The *pn*-junction can be represented by an equivalent circuit, and its voltage–current characteristics can be plotted.

1-1 The Atom

The atom is believed to consist of a central *nucleus* surrounded by orbiting *electrons* (see Fig. 1-1). Thus, it may be compared to a planet with orbiting satellites. Just as satellites are held in orbit by an attractive force of gravity due to the mass of the planet, so each electron is held in orbit by an *electrostatic* force of attraction between it and the nucleus.

The electrons each have a negative electrical charge of 1.602×10^{-19} *coulombs* (C), and some particles within the nucleus have a positive charge of the same magnitude. Since opposite charges attract, a force of attraction exists between the oppositely charged electron and nucleus. Compared to the mass of the nucleus, electrons are relatively tiny particles of almost negligible mass. In fact, we may think of them simply as little particles of negative electricity having no mass at all.

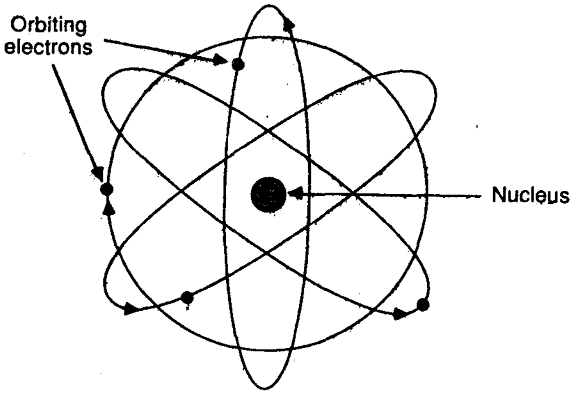


Figure 1-1 The atom consists of a central nucleus surrounded by orbiting electrons. Electrons have a negative charge, and the protons in the nucleus have a positive charge.

The nucleus of an atom is largely a cluster of two types of particles, *protons* and *neutrons*. Protons have a positive electrical charge, equal in magnitude (but opposite in polarity) to the negative charge on an electron. A neutron has no charge at all. Protons and neutrons each have masses about 1800 times the mass of an electron. For a given atom, the number of protons in the nucleus normally equals the number of orbiting electrons.

Since the protons and orbital electrons are equal in number and equal and opposite in charge, they neutralize each other electrically. For this reason, all atoms are normally electrically neutral. If an atom loses an electron, it has lost some negative charge. Therefore, it becomes *positively* charged and is referred to as a *positive ion*. Similarly, if an atom gains an additional electron, it becomes *negatively* charged and is termed a *negative ion*.

The differences among atoms consist largely of dissimilar numbers and arrangements of the three basic types of particles. However, all electrons are identical, as are all protons and all neutrons. An electron from one atom could replace an electron in any other atom. Different materials are made up of different types of atoms, or differing combinations of several types of atoms.

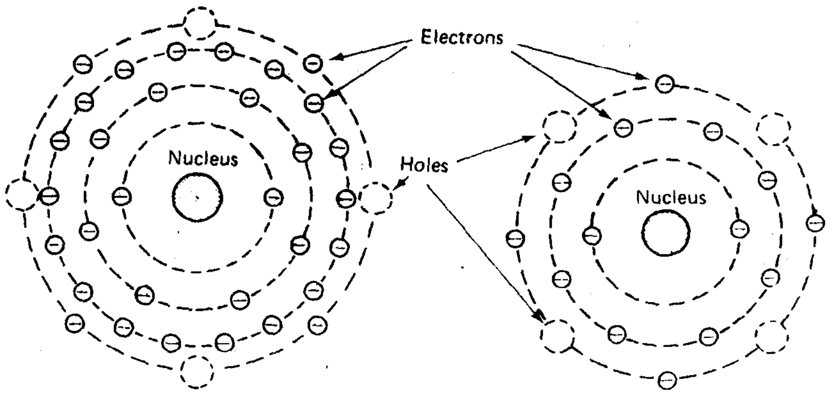
The number of protons in an atom is referred to as the *atomic number* of the atom. The *atomic weight* is approximately equal to the total number of protons and neutrons in the nucleus of the atom. The atom of the semiconductor material silicon has 14 protons and 14 neutrons in its nucleus, as well as 14 orbital electrons. Therefore, the atomic number for silicon is 14, and its atomic weight is approximately 28.

1-2 Electron Orbits and Energy Levels

Atoms may be conveniently represented by the two-dimensional diagrams shown in Fig. 1-2. It has been found that electrons can occupy only certain orbital rings or *shells* at fixed distances from the nucleus, and that each shell can contain only a particular number of electrons. The electrons in the outer shell determine the electrical (and chemical) characteristics of each particular type of atom. These electrons are usually referred to as *valence electrons*. An atom may have its outer or *valence shell* completely filled or only partially filled.

The atoms of two important semiconductors, *silicon* (Si) and *germanium* (Ge), are illustrated in Fig. 1-2. It is seen that each of these atoms has four electrons in a valence shell that can contain a maximum of eight. Thus, we say that their valence shells have four electrons and four *holes*. A *hole* is defined simply as an absence of an electron in a shell where one could exist. Even though their valence shells have four holes, both silicon and germanium atoms are electrically neutral, because the total number of orbital (negatively charged) electrons equals the total number of (positively charged) protons in the nucleus.

The closer an electron is to the nucleus, the stronger are the forces that bind it Each shell has an *energy level* associated with it which represents the



(a) Germanium atom (b) Silicon atom

Figure 1-2 Two-dimensional representation of silicon and germanium atoms. Each of these atoms has four electrons and four holes in its valence (or outer) shell.

amount of energy that would have to be supplied to extract an electron from the shell. Since the electrons in the valence shell are farthest from the nucleus, they require the least amount of energy to extract them from the atom. Conversely, those electrons closest to the nucleus require the greatest energy application to extract them from the atom.

The energy levels considered above are measured in *electron volts* (eV). An *electron volt* is defined as the amount of energy required to move one electron through a potential difference of one volt.

1-3 Energy Bands

So far, the discussion has concerned a system of electrons in one isolated atom. The electrons of an isolated atom are acted upon only by the forces within that atom. However, when atoms are brought closer together, as in a solid, the electrons come under the influence of forces from other atoms. Under these circumstances, the energy levels that may be occupied by electrons merge into bands of energy levels. Within any given material there are two distinct *energy bands* in which electrons may exist, the *valence band* and the *conduction band*. Separating these two bands is an *energy gap* in which no electrons can normally exist. This gap is termed the *forbidden gap*. The valence band, conduction band, and forbidden gap are shown diagrammatically in Fig. 1-3.

Electrons within the conduction band have become disconnected from atoms and are drifting around within the material. Conduction band electrons may be easily moved around by the application of relatively small amounts of energy. Much larger amounts of energy must be applied to extract an electron from the valence band or to move it around within the valence band. Electrons in the valence band are usually in normal orbit around a nucleus. For any given type of material, the forbidden gap may be large, small, or nonexistent. The distinction between conductors, insulators, and semiconductors is largely concerned with the relative widths of the forbidden gap.

It is important to note that the energy band diagram is simply a graphic representation of the energy levels associated with electrons. To repeat, those electrons in the valence band are actually in orbit around the nucleus of an atom; those in the conduction band are drifting about in the spaces between atoms.

1-4 Conduction in Solids

Conduction occurs in any given material when an applied voltage causes electrons within the material to move in a desired direction. This may be due to one or both of two processes, *electron motion* and *hole transfer*. In electron

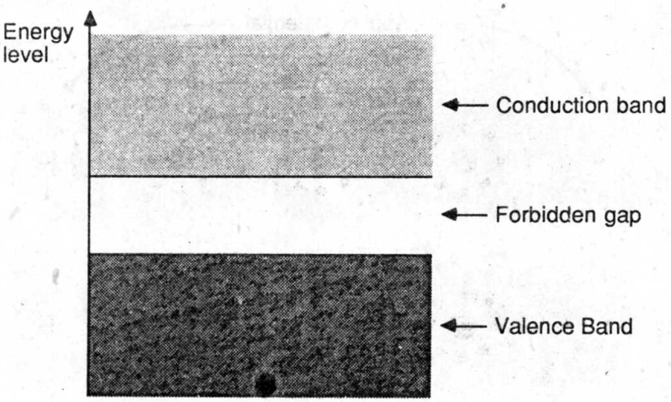


Figure 1-3 Energy band diagram, showing energy levels at which electrons may exist in a solid. Those electrons in orbit around atoms occupy the valence band. Those drifting free in the spaces between atoms have an energy level in the conduction band. Electrons normally cannot exist at an energy level represented by the forbidden gap between the conduction and valence bands.

motion, *free electrons* in the conduction band are moved under the influence of the applied electric field. Since electrons have a negative charge, they are repelled from the negative terminal of the applied voltage and attracted toward the positive terminal. Hole transfer involves electrons which are still attached to atoms, i.e., those in the valence band.

If some of the energy levels in the valence band are not occupied by electrons, there are holes where electrons could exist. An electron may jump from one atom to fill the hole in another atom. When it jumps, the electron leaves a hole behind it, and thus the hole has moved in a direction opposite to that of the electron. In this way a current flows which may be said to be due to hole movement.

In Fig. 1-4 there are no free electrons. However, those electrons in orbit around atoms experience a force of attraction to the positive terminal of an applied potential, and repulsion from the negative terminal. Consequently, an electron can be made to jump from one atom to fill the hole in another atom, so long as it is moving toward the positive terminal. In Fig. 1-4(a), an electron is made to jump from atom y to atom x. The hole in the valence shell of atom x is now filled, and a hole is left in the valence shell of atom y [Fig. 1-4(b)]. If an electron now jumps from atom z to fill the hole in y, a hole is left in the valence shell of z [Fig. 1-4(c)]. Thus, the hole has moved from atom x to atom y to atom z.