Electronic Devices, Circuits, and Systems

THIRD EDITION

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Dedicated to my mother
Smilja
to whom I am grateful
for much more than my existence

Michael M. Cirovic

Preface

The age in which we live has been termed the *Age of Technology*. Electronics has played a major role in this technology: It has provided us with the hardware to improve communciation, to enable us to explore the universe, to help physicians provide us with better health care, and to process huge amounts of information and with data to liberate us from the more mundane tasks. The list of accomplishments, as well as future possibilities, is unending. However, in some cases, the hardware of the technological revolution has created problems that are not easily solved. The future technologist, unlike his or her predecessor, must be more aware of and concerned with the consequences of technology on people and their environment.

The purpose of this book is threefold: first, to introduce a variety of semiconductor devices (integrated circuits and discrete devices), their basic operation, and their characteristics; second, to illustrate how these devices are used in simple electronic circuits, as well as how these circuits are analyzed and designed; third, to present complex electronic systems as simple extensions and examples of the use of devices and simple circuits. The prerequisites for understanding the material are basic college mathematics (algebra) and a basic course in electronic circuits.

Part I presents the basic physics and physical principles that make understanding the operation of electronic devices possible. This is a brief description, not a mathematical discussion, leading to the terminal characteristics of devices. The terminal characteristics directly lead to and suggest biasing schemes that follow. With the devices properly biased, terminal characteristics under signal conditions are presented, leading to the use of models and equivalent circuits in the systematic analysis of circuits containing devices.

Part II deals with applying the devices introduced in Part I in simple circuits. Methods of analysis stressing approximations and practical considerations are used, and some design problems are illustrated.

In Part III more complex electronic circuits and systems are described. In some cases, actual circuits are examined; in other cases, block diagrams are used.

By using this three-tiered building-block approach, the reader is able to move from simple, basic concepts to complex systems and is able to see how even the most complex electronic system is a logical extension of very simple circuits.

The third edition of *Electronic Devices, Circuits, and Systems* (formerly titled *Basic Electronics*) has undergone an extensive content revision. Many linear integrated circuits have been added, as have several power MOSFET devices. New to this edition are topics on fiber optic devices, heat sinks, electric static discharge (ESD), operational amplifiers, and IC thyristor triggers.

In the 13 years since the first edition was published, most electronics curricula have created separate courses in digital and communication circuits and systems. In response to the evolution of the electronics curriculum, topics dealing with communication circuits as well as digital circuits have been deleted from the text.

We would be remiss in not acknowledging six reviewers whose valued suggestions have shaped the third edition of the text. Our thanks to Russell Puckett, P.E., Texas A & M University; William Campas, John Tyler Community College; Roger Scheunemann, Group III Electronics; Conrad Zalace, GM Hughes Electron Dynamics Division; Stephen Cheshier, Ph.D., Southern Technical College; and Gary Lyon, Mesa Community College. We are also grateful to the manufacturers who provided technical data sheets and illustrative materials.

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Part I

Devices

Electronic circuits use many different components. Besides resistors, capacitors, and inductors, there is a large group of active components called *electronic devices*, or simply devices. In circuits, these devices exist in two different forms: either as a separate component, called a *discrete component*, or as a unit with many components in one package, called an *integrated circuit.* In either form, the electronic device is usually the most important and, at the same time, the most complicated part of a circuit. You will be able to understand and fully use electronic circuits only if you first study each device in the circuit by itself and then as it relates to the whole circuit. Once you understand how the device works, predicting the operation of a circuit containing the device becomes relatively easy and straightforward.

Part I studies various semiconductor devices so that a knowledge of their terminal characteristics is gained along with an understanding of these characteristics.

Chapter 1

Semiconductor Physics

The rapid advances in semiconductor technology from the 1950s to present have revolutionized electronics. In replacing vacuum tubes, semiconductor devices brought smaller size, increased lifetime, lower power consumption, lower operating temperatures, and lower costs. To understand how these results were possible, we have to examine the physics of semiconductors. Our treatment will be descriptive rather than mathematical. The physical principles involved will be emphasized; not their formal mathematical descriptions.

1.1 CLASSIFYING MATTER

The ability of a material to conduct electricity or to sustain an electric current will be used as a means of classifying matter. Conduction takes place as a result of the motion of charged particles, usually *free electrons*. Thus, the ability of any material to conduct is directly proportional to the number of charged particles that can be set in motion within the material. Materials that have relatively large numbers of free electrons (such as metals) are very capable of sustaining an electric current. These materials are called *conductors*. Other materials that do not readily sustain an electric current under normal conditions are called *insulators*. Insulators have very few or no free electrons. It should be realized that the terms *conductor* and *insulator* are not absolute; that is, some conductors do not conduct as well as other conductors, while some insulators do not insulate as well as other insulators.

1.1.1 Shell Structure

The electrical conductivity of a material depends on the structure of the individual atoms, as well as the manner in which the atoms are arranged within the material. All matter is made up of atoms in assorted configurations. Each atom has its electrons arranged in shells or orbits around the nucleus. In the electrically neutral atom, the positive charge of the nucleus is balanced by an equal negative charge

TABLE 1.1 SUMMARY OF SHELL STRUCTURE

Shell number (letter)	Subshell number (letter)	Maximum number of electrons allowed	Total possible in shell
1(*L*)	1(1*s*)	2	2
2(*M*)	1(2*s*)	2	8
	2(2*p*)	6	
3(*N*)	1(3*s*)	2	
	2(3*p*)	6	18
	3(3*d*)	10	

of the electrons in orbit around the nucleus. The distinguishing factor among atoms of different materials is the size of the nucleus and the number of electrons in orbit around the nucleus. As an example, an oxygen atom has a large nucleus with 16 electrons in orbit; in contrast, a hydrogen atom has a small nucleus with only one electron in orbit.

In atomic structure, there is a specific scheme, called *shells*, for the arrangement of electrons into orbits. Furthermore, there is a prescribed maximum number of electrons that can be sustained in any one shell or orbit at any given time. It should be noted that the shells are divided into subshells (suborbits), each of which can sustain a maximum allowed number of electrons. This structure, together with the number of electrons allowed for the first three shells, is given in Table 1.1. Perhaps the easiest way to visualize electrons in a shell is to think of each electron as requiring its own little space, with only a limited number of spaces in each shell.

The shells and subshells closest to the nucleus are filled first, until all the electrons for that particular atom are accommodated. For example, in a hydrogen atom, the one and only electron is found in the *L* shell (the first shell). In an oxygen atom, its 16 electrons are distributed as follows: 2 in the first shell (the *L* shell); 8 in the second shell (2 in the 2s subshell, 6 in the 2p subshell); and 6 in the third shell (2 in the 3s subshell, 4 in the 3p subshell). Thus, the pattern is clear. The innermost shells and subshells are filled completely before any of the other shells. The outermost shell containing electrons is called the *valence shell*, and it plays the important role of determining the electrical as well as the chemical properties of elements.

Using aluminum, with a total of 13 electrons as an example, the shell structure is: $1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^1$ (where the superscript numbers indicate the number of electrons in that particular subshell). The valence shell is incomplete and contains three electrons. For the valence shell to be complete, it needs either to gain five electrons or to give up three electrons. In either case, the aluminum atom becomes *ionized*. (As previously noted, an atom is electrically neutral but when it gains or loses electrons, it develops a net charge and is said to be ionized.)

Aluminum is known to be trivalent; that is, it gives up three electrons when reacting with other elements. The reason for giving up three and not acquiring five electrons is that less energy is involved in liberating three electrons simply because of the lower number of electrons involved.

Aluminum is a good electrical conductor because of the three loosely bonded valence electrons. The energy binding the three valence electrons to the nucleus of the aluminum atom is weak and only a small amount of energy is needed to liberate the three valence electrons. The energy present at room temperature is sufficient to free the valence electrons for electrical conduction. A bar of aluminum is made up of literally billions of atoms and at room temperature countless free electrons are available for conduction.

A good insulator results from elements that have filled or completed valence shells. In these cases, no electrons are freed at room temperature because of the strong binding forces between the electrons in the filled shells and the nucleus. A material made up of such elements is called *inert*; it does not provide any free electrons that could take part in conduction.

1.1.2 Energy Bands

The difference in the binding energy of valence electrons in the valence shell is used as the basis for another means of classifying materials. An electron in the valence shell is said to have energy corresponding to the valence band of energy or, simply, *valence band.** However, as a result of acquiring a specific amount of additional energy, an electron in the valence shell becomes free of the nucleus; with its new energy, an electron is characterized as being in the conduction band of energy or, simply, *conduction band.* Differentiation among materials can be made on the basis of the amount of energy needed to liberate a single valence electron from the influence of the nucleus. The amount of energy between the highest energy in the valence band, labeled E_v, and the lowest energy in the conduction band, labeled E_c, is a characteristic of the material and is called the *energy gap*, labeled E_g. From these definitions, we can write

$$E_g = E_c - E_v \tag{1.1}$$

In a metal or other good electrical conductor at room temperature, there is an overlap between the conduction and valence bands, as shown in Figure 1.1. Consequently, in a conductor, many electrons are free to take part in conduction and very little energy is needed to sustain a sizable electric current.

In an insulator, the energy gap is large; that is, the conduction and valence bands are far apart, as shown in Figure 1.1. As a result, a large amount of energy is required to liberate even a small number of electrons that could then contribute to conduction.

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* Extremely large numbers of electrons are involved in even small samples, and each electron has a discrete amount of energy slightly different from any other electron. The range of energy possessed by all the electrons in all the valence shells constitutes a dense set of energy values called a *band*—in this case, a valence band.

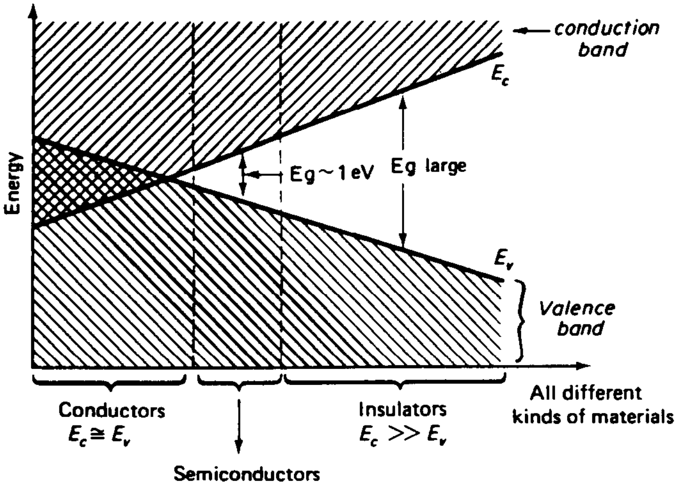

Figure 1.1 Classification of matter on the basis of conductivity.

1.2 SEMICONDUCTORS

From Figure 1.1 we see that there is no sharp dividing line between conductors and insulators; there are materials that are neither good conductors nor good insulators. These materials are called *semiconductors* and are characterized by energy gaps on the order of 1 electron volt (1 eV), as shown in Figure 1.1. The principle semiconductor material used in electronics is silicon (Si) with germanium (Ge) as a secondary material.

An atom of silicon has 14 electrons, and its electron-shell configuration is $1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^2$. Because the third shell is incomplete, it is the valence shell. In order for the third shell to be complete, it must either acquire four electrons in its 3p subshell or lose the four electrons that it already has in the 3s and 3p subshells. In either gaining or losing electrons, exactly the same number of electrons is involved; therefore, exactly the same energy is involved and neither process is more likely to occur. Thus, silicon neither acquires nor gives up electrons. Instead, each silicon atom enters into a unique sharing of its four valence electrons, called *covalent bonding*.

1.2.1 Covalent Bonding

In covalent bonding, each silicon atom shares two electrons with each of its four nearest neighbors. As shown in Figure 1.2, each silicon atom in the *crystal lattice* is connected by means of a single *covalent bond* (2 shared electrons) to each of four other atoms located at the corners of a regular tetrahedron. This basic structure is repeated millions of times in a crystal and is illustrated schematically in Figure 1.3.

The crystal structure for germanium is similar to that of silicon. Its valence