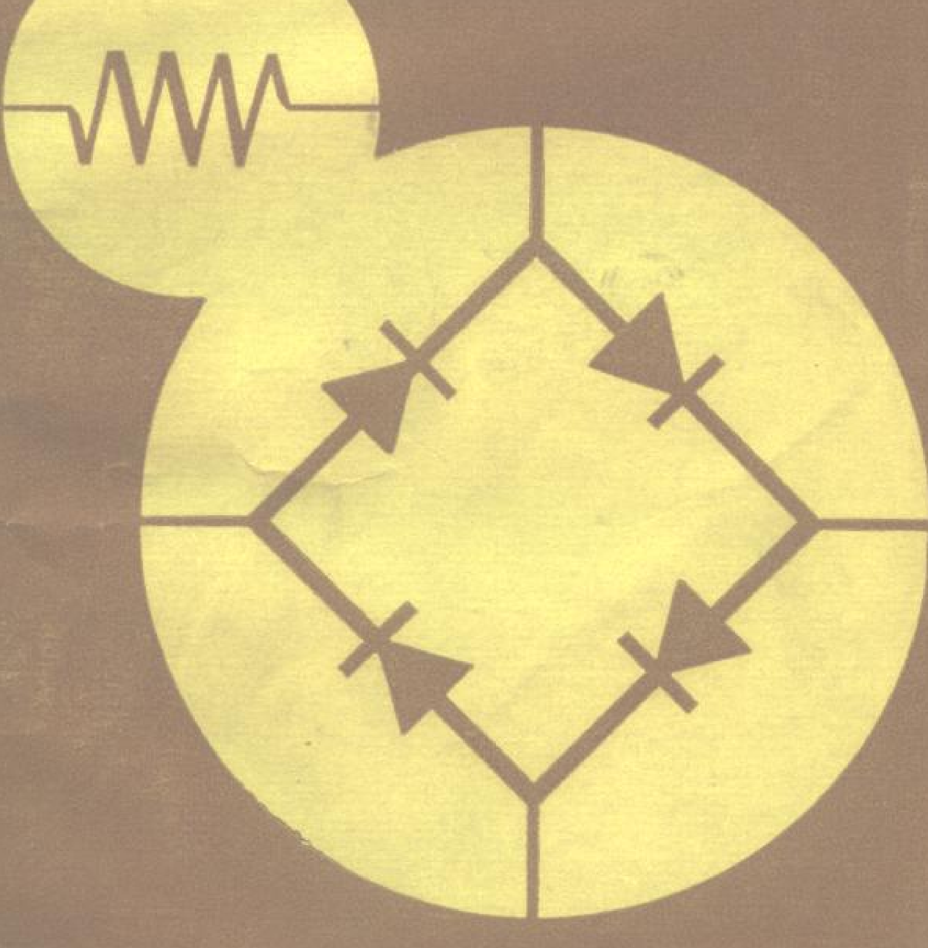
Fundamentals of Electronic Devices



DAVID A. BELL

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David A. Bell

Lambton College of
Applied Arts and Technology
Sarnia, Ontario, Canada

RESTON PUBLISHING COMPANY, INC.
Reston, Virginia 22090

A Prentice-Hall Company

Library of Congress Cataloging in Publication Data

Bell, David, 1930–
Fundamentals of electronic devices.

1. Semiconductors. I. Title.
TK7871.85.B3786 621.3815 74-16377
ISBN 0-87909-276-9

Reston Publishing Company, Inc.
A Prentice-Hall Company
Box 547
Reston, Virginia 22090

10 9 8 7 6 5 4 3 2 1

Printed in the United States of America.

Preface

My objectives in this book are to clearly explain the operation of all important electronic devices in general use today and, also, to give the reader a thorough understanding of the characteristics, parameters, circuit applications, and limitations of each device at a two-year college level.

The text commences with the study of basic semiconductor theory and *pn*-junction theory which is essential for an understanding of solid-state devices. A separate chapter explains the semiconductor diode. Diode characteristics, parameters, equivalent circuits, graphical analysis, applications as a rectifier, and the diode data sheets are all covered in detail.

Bipolar junction transistor theory is treated in depth in Chap. 4, with the origin of *r*-parameters, *h*-parameters, and both equivalent circuits explained. In Chap. 5, the basic transistor circuits are analyzed for voltage gain, current gain, power gain, input impedance, and output impedance. The analysis is performed by *h*-parameters, and simplifying approximations are used throughout. Chapter 6 is devoted to transistor biasing techniques, while transistor manufacturing methods and data sheets are among the topics covered in Chap. 7. Transistor power dissipation, frequency response, noise, and switching are also treated in Chap. 7.

Chapters 8 and 9, on Zener and tunnel diodes, cover such topics as Zener diode voltage regulators and tunnel diode amplifiers. The next three chapters cover field effect transistors. Chapter 10 explains the theory of operation of the various types of FET's, as well as FET construction, data sheet, and equivalent circuit. Basic FET circuits are studied in Chap. 11, and FET biasing is treated in Chap. 12. SCR's, UJT's, optoelectronic devices, miscellaneous devices, and integrated circuits are dealt with in Chaps. 13 through 17. Among the topics included are programmable UJT's, solar cells, liquid-crystal cells, piezoelectric crystals, VVC diodes, and IC amplifiers. Since electron tubes are still in wide use, the final chapter covers its varied forms: the vacuum diode, the vacuum triode, triode circuits, the tetrode, the pentode, the pentagrid converter, and, of course, the cathode ray tube.

Many examples are included in the text to introduce the student to applications of the device under study. A glossary of important terms and a set of review questions are provided at the end of each chapter. The mathematics level throughout does not go beyond algebraic equations and logarithms, simply because no higher math is necessary to fulfill the purpose of the book. It is expected that students will have already studied basic electricity, or that they will be studying this subject concurrently with their devices course.

It is hoped that this book will prove useful both for the study of electronics and as a reference text.

DAVID A. BELL

Contents

CHAPTER 1

Basic Semiconductor Theory

1-1 INTRODUCTION

The function of an *electronic device* is to control the movement of *electrons*. The first step in a study of such devices is to understand the electron (or what it is believed to be), and how it is associated with the other components of the atom. After such an understanding is reached the bonding forces holding atoms together within a solid, and the movement of electrons from one atom to another must be investigated. A result of the investigation is that the differences between *conductors*, *insulators*, and *semiconductors*, and the special properties of semiconductors become clear.

1-2 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 satellites in orbit around it. 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. As in the case of the satellites, the force of attraction is balanced by the centrifugal force due to the motion of the electrons around the nucleus [Fig. 1–1(b) and (c)].

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.

The nucleus of an atom is largely a cluster of two types of particles, *protons* and *neutrons* (Fig. 1–2). 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

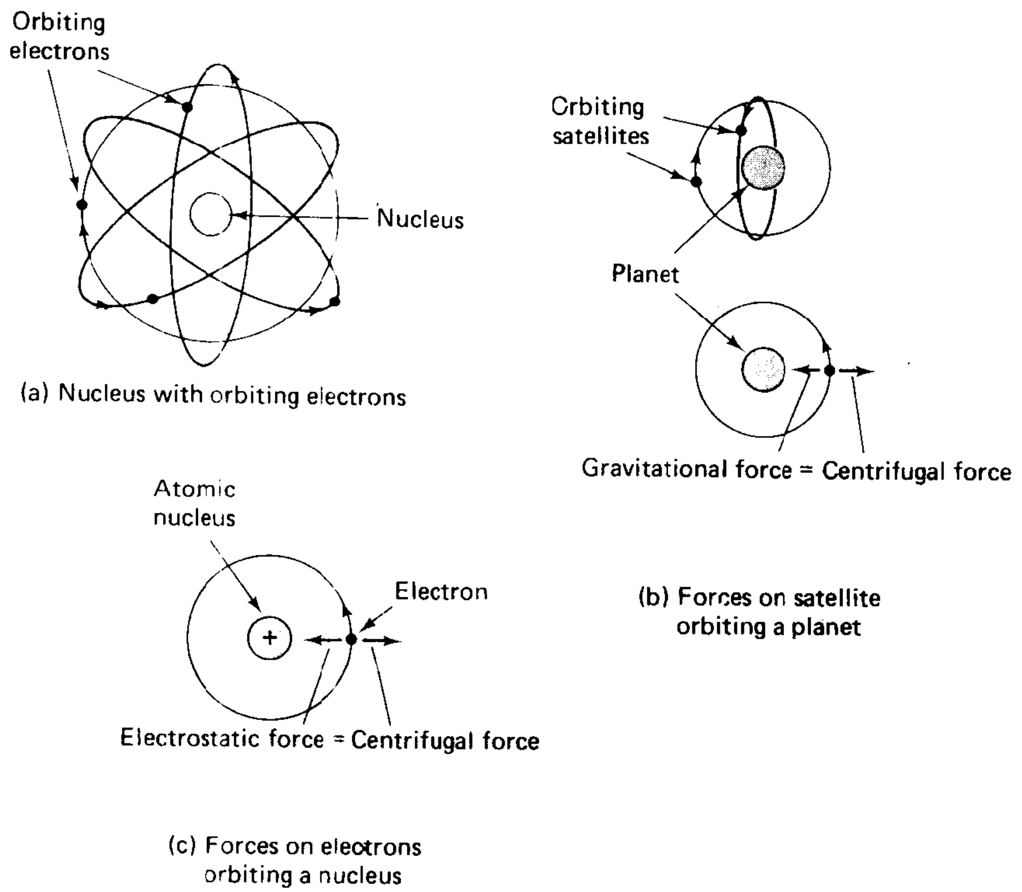

FIG. 1-1 Planetary atom.

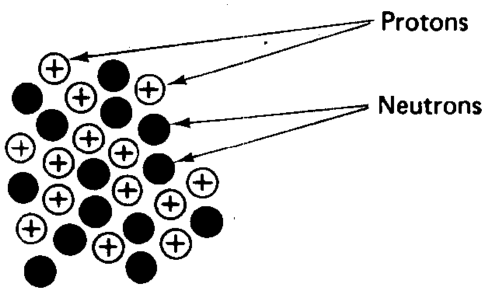

FIG. 1-2 Nucleus of a silicon atom.

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 between 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 (or electrons) 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 element *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.

1-3 ELECTRON ORBITS AND ENERGY LEVELS

Atoms may be conveniently represented by the two-dimensional diagrams shown in Fig. 1–3. 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.

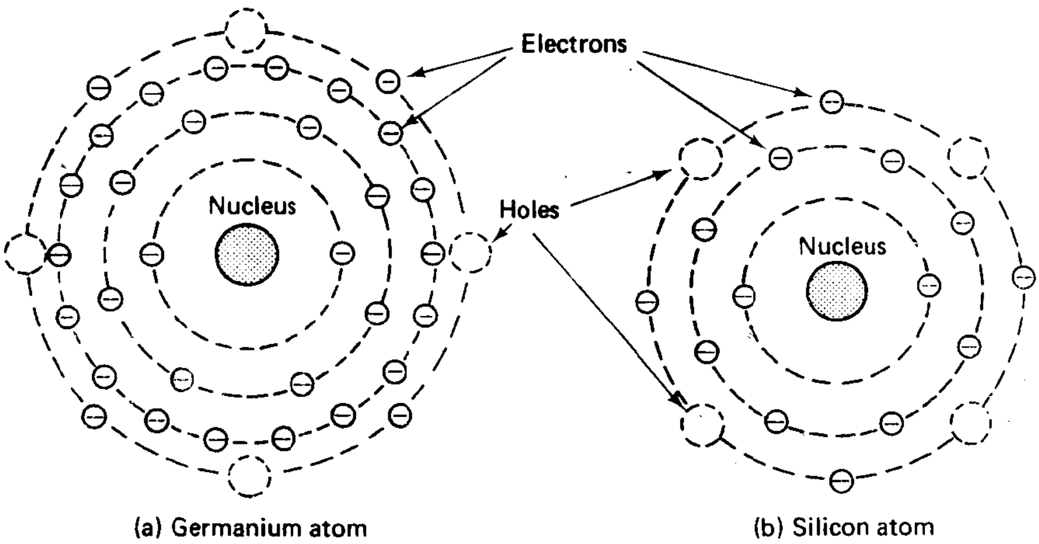

FIG. 1-3 Two-dimensional representation of silicon and germanium atoms.

The atoms of two important semiconductors, *silicon* (Si) and *germanium* (Ge), are illustrated in Fig. 1–3. 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 still electrically neutral, because the total number of orbital electrons equals the total number of 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 amount of energy that would have to be supplied to extract an electron from the shell. Since the electrons in the valence shell are furthest 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.

1-4 ENERGY BANDS

So far the discussion has concerned a system of electrons around 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

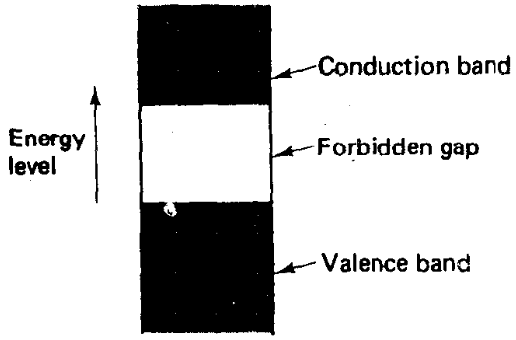

FIG. 1-4 Energy band diagram.

solid, the electrons come under the influence of forces from other atoms. 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. 1-4.

Electrons in the conduction band have escaped from their atoms, or are only weakly held to the nucleus. Conduction band electrons may be easily moved around within the material, 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.

1-5 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 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 towards 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 we say that the hole has moved in the opposite direction to the electron. In this way a current flows which may be said to be due to hole movement.

In Fig. 1–5(a), the applied potential causes an electron to jump from atom *y* to atom *x*. In doing so, it fills the hole in the valence shell of atom *x*, and leaves a hole behind it in atom *y* as shown in Fig. 1–5(b). If an electron now jumps from atom *z*, under the influence of the applied potential, and fills the hole in the valence shell of atom *y*, it will leave a hole in atom *z* [Fig. 1–5(c)]. Thus, the hole has been caused to move from atom *x* to atom *y* to atom *z*.

Holes may be thought of as positive particles, and as such they move through an electric field in a direction opposite to that of the electrons; i.e., positive particles are attracted towards the negative terminal of an applied voltage. It is more convenient to think in terms of hole movement, rather than in terms of electrons jumping from atom to atom.

Since the flow of electric current is constituted by the movement of electrons in the conduction band and holes in the valence band, electrons and holes are referred to as *charge carriers*. Each time a hole moves, an electron must be supplied with sufficient energy to enable it to escape from its atom. Free electrons require less application of energy than holes to move them, because they are already disconnected from their atoms. For this reason, electrons have *greater mobility* than holes.

The unit of electric current is the *ampere* (A). An ampere is defined as

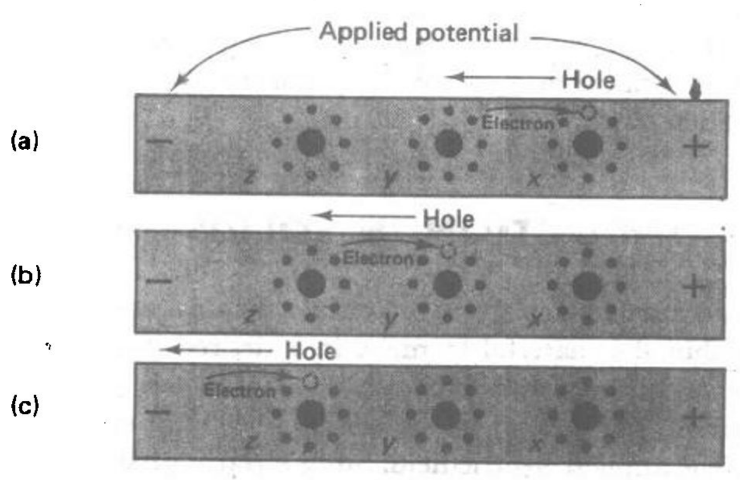

FIG. 1–5 Conduction by hole transfer. (a) Electron jumps from atom *y* to atom *x*. (b) It fills the hole in atom *x* and leaves a hole in atom *y*. (c) If an electron jumps from atom *z* to atom *y*, it will leave a hole in atom *z*.