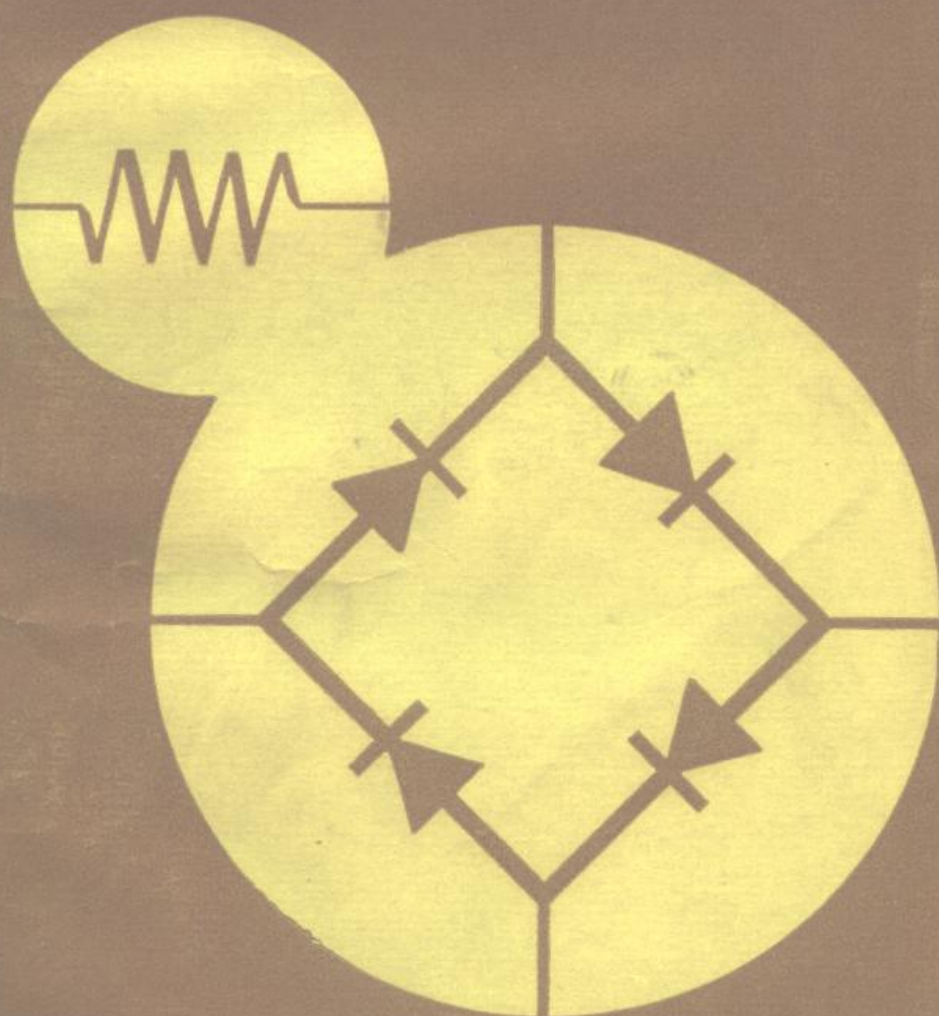


# Fundamentals of Electronic Devices



DAVID A. BELL

# **Fundamentals of Electronic Devices**

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# 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,

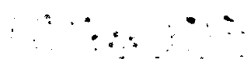
while transistor manufacturing methods and data sheets are among the topics covered in Chap. 7. Transistor power dissipation, frequency response, noise, and switching are also treated in Chap. 7.

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



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# Contents

## PREFACE

xi

## **Chapter 1**    **BASIC SEMICONDUCTOR THEORY**

1

- 1-1      Introduction, 1
- 1-2      The Atom, 1
- 1-3      Electron Orbits and Energy Levels, 3
- 1-4      Energy Bands, 4
- 1-5      Conduction in Solids, 5
- 1-6      Conductors, Insulators, and Semiconductors, 7
- 1-7      Bonding Forces Between Atoms, 8
- 1-8      Semiconductor Doping, 9
- 1-9      Effects of Heat and Light, 11
- 1-10     Drift Current and Diffusion Current, 12
- Glossary of Important Terms, 14*
- Review Questions, 16*

<b>Chapter 2</b>	<b><i>pn</i>-JUNCTION THEORY</b>	<b>18</b>
2-1	Introduction, 18	
2-2	The <i>pn</i> -Junction, 18	
2-3	Reverse Biased Junction, 22	
2-4	Forward Biased Junction, 24	
2-5	Temperature Effects, 26	
2-6	Junction Capacitance, 28	
2-7	Junction Equivalent Circuit, 28	
	<i>Glossary of Important Terms</i> , 29	
	<i>Review Questions</i> , 30	
<b>Chapter 3</b>	<b>THE SEMICONDUCTOR DIODE</b>	<b>32</b>
3-1	Introduction, 32	
3-2	Diode Symbol and Appearance, 32	
3-3	Diode Fabrication, 35	
3-4	Diode Characteristics and Parameters, 35	
3-5	Graphical Analysis of Diode Circuit, 37	
3-6	Diode Piecewise Linear Characteristics, 41	
3-7	Diode Equivalent Circuit, 43	
3-8	Half-Wave Rectification, 44	
3-9	Full-Wave Rectification, 50	
3-10	Diode Switching Time and Frequency Response, 53	
3-11	Diode Data Sheet, 55	
	<i>Glossary of Important Terms</i> , 57	
	<i>Review Questions</i> , 59	
<b>Chapter 4</b>	<b>THE JUNCTION TRANSISTOR</b>	<b>61</b>
4-1	Introduction, 61	
4-2	Transistor Operation, 61	
4-3	Transistor Currents, 66	
4-4	Transistor Symbols and Voltages, 69	
4-5	Common Base Characteristics, 70	
4-6	Common Emitter Characteristics, 74	
4-7	Common Collector Characteristics, 78	
4-8	Transistor T-Equivalent Circuit and $r$ -Parameters, 80	
4-9	$h$ -Parameters, 81	
	<i>Glossary of Important Terms</i> , 86	
	<i>Review Questions</i> , 88	
<b>Chapter 5</b>	<b>BASIC TRANSISTOR CIRCUITS</b>	<b>90</b>
5-1	Introduction, 90	
5-2	Common Emitter Circuit, 90	
5-3	Common Emitter $h$ -Parameter Analysis, 92	
5-4	Common Collector Circuit, 99	
5-5	Common Collector $h$ -Parameter Analysis, 100	

- 5-6 Common Base Circuit, 105
- 5-7 Common Base  $h$ -Parameter Analysis, 107
- 5-8 Cascaded Common Emitter Circuits, 113
- Glossary of Important Terms*, 115
- Review Questions*, 116

## **Chapter 6 TRANSISTOR BIASING 118**

- 6-1 Introduction, 118
- 6-2 The dc Load Line and Bias Point, 119
- 6-3 Fixed Current Bias, 123
- 6-4 Collector-to-Base Bias, 125
- 6-5 Emitter Current Bias (or Self Bias), 127
- 6-6 Comparison of Basic Bias Circuits, 131
- 6-7 Thermal Stability, 131
- 6-8 ac Bypassing and ac Load Line, 134
- Glossary of Important Terms*, 138
- Review Questions*, 139

## **Chapter 7 TRANSISTOR CONSTRUCTION, SPECIFICATIONS AND PERFORMANCE 141**

- 7-1 Introduction, 141
- 7-2 Effects of Transistor Construction on Electrical Performance, 142
- 7-3 Processing of Semiconductor Materials, 143
- 7-4 Alloy and Microalloy Transistors, 146
- 7-5 Mesa Transistors, 148
- 7-6 Diffused Planar and Annular Transistors, 150
- 7-7 Transistor Packaging, 151
- 7-8 The Transistor Data Sheet, 153
- 7-9 Power Dissipation, 157
- 7-10 Decibels and Frequency Response, 159
- 7-11 Transistor Noise, 165
- 7-12 Transistor Switching, 171
- Glossary of Important Terms*, 177
- Review Questions*, 179

## **Chapter 8 ZENER DIODES 181**

- 8-1 Introduction, 181
- 8-2 Zener and Avalanche Breakdown, 182
- 8-3 Zener Diode Characteristic and Parameters, 184
- 8-4 Compensated Reference Diodes, 185
- 8-5 Zener Diode Voltage Regulator, 188
- 8-6 Regulator with Reference Diode, 193
- 8-7 Other Zener Diode Applications, 193
- Glossary of Important Terms*, 195
- Review Questions*, 196

5504909



<b>Chapter 9</b>	<b>THE TUNNEL DIODE</b>	<b>198</b>
9-1	Introduction, 198	
9-2	Theory of Operation, 198	
9-3	Tunnel Diode Symbol, Characteristics, and Parameters, 203	
9-4	Piecewise Linear Characteristics, 204	
9-5	Tunnel Diode Equivalent Circuit, 206	
9-6	Tunnel Diode Parallel Amplifier, 206	
9-7	Gain Formula for a Parallel Amplifier, 209	
9-8	Practical Parallel Amplifier Circuit, 210	
9-9	Graphical Analysis of a Parallel Amplifier, 213	
9-10	Tunnel Diode Series Amplifier, 215	
9-11	Gain Formula for Series Amplifier, 217	
9-12	Tunnel Diode Switch, 217	
9-13	Tunnel Diode Biasing, 219	
	<i>Glossary of Important Terms</i> , 220	
	<i>Review Questions</i> , 221	
<b>Chapter 10</b>	<b>FIELD EFFECT TRANSISTORS</b>	<b>223</b>
10-1	Introduction, 223	
10-2	Principle of the $n$ -Channel JFET, 223	
10-3	Characteristics of $n$ -Channel JFET, 225	
10-4	The $p$ -Channel JFET, 230	
10-5	JFET Data Sheet and Parameters, 231	
10-6	JFET Construction, 239	
10-7	The Insulated Gate FET or MOSFET, 240	
10-8	FET Equivalent Circuit, 245	
	<i>Glossary of Important Terms</i> , 246	
	<i>Review Questions</i> , 248	
<b>Chapter 11</b>	<b>BASIC FET CIRCUITS</b>	<b>250</b>
11-1	Introduction, 250	
11-2	The Common Source Circuit, 250	
11-3	ac Analysis of Common Source Circuit, 252	
11-4	The Common Drain Circuit, 255	
11-5	ac Analysis of Common Drain Circuit, 257	
11-6	The Common Gate Circuit, 260	
11-7	ac Analysis of the Common Gate Circuit, 261	
	<i>Glossary of Important Terms</i> , 264	
	<i>Review Questions</i> , 265	
<b>Chapter 12</b>	<b>FET BIASING</b>	<b>267</b>
12-1	Introduction, 267	
12-2	dc Load Line and Bias Point, 267	
12-3	Spread of Characteristics and Fixed Bias Circuit, 270	
12-4	Self Bias, 271	

- 12-5 Self Bias with External Voltage, 274
- 12-6 Drain-to-Gate Bias, 277
- 12-7 Biasing MOSFETS, 279
- 12-8 Design of FET Bias Circuits, 285  
*Glossary of Important Terms*, 287  
*Review Questions*, 288

### **Chapter 13 THE SILICON CONTROLLED RECTIFIER**

**293**

- 13-1 Introduction, 293
- 13-2 SCR Operation, 294
- 13-3 SCR Characteristics and Parameters, 296
- 13-4 SCR Specifications, 299
- 13-5 SCR Control Circuits, 301
- 13-6 The TRIAC and DIAC, 305
- 13-7 Other Four-Layer Devices, 307  
*Glossary of Important Terms*, 311  
*Review Questions*, 313

### **Chapter 14 THE UNIJUNCTION TRANSISTOR**

**315**

- 14-1 Introduction, 315
- 14-2 Theory of Operation, 315
- 14-3 UJT Characteristics, 317
- 14-4 UJT Parameters and Specification, 319
- 14-5 UJT Fabrication Methods, 322
- 14-6 UJT Relaxation Oscillator, 323
- 14-7 UJT Control of SCR, 327
- 14-8 Programmable Unijunction Transistor, 328  
*Glossary of Important Terms*, 330  
*Review Questions*, 331

### **Chapter 15 OPTOELECTRONIC DEVICES**

**332**

- 15-1 Introduction, 332
- 15-2 Photomultiplier Tube, 333
- 15-3 The Photoconductive Cell, 335
- 15-4 The Photodiode, 340
- 15-5 The Solar Cell, 343
- 15-6 The Phototransistor, 346
- 15-7 The Photofet, 349
- 15-8 Light-Emitting Diodes, 350
- 15-9 Liquid-Crystal Displays, 352
- 15-10 Optoelectronic Coupler, 355  
*Glossary of Important Terms*, 355  
*Review Questions*, 357

<b>Chapter 16</b>	<b>MISCELLANEOUS DEVICES</b>	<b>360</b>
16-1	Piezoelectricity, 360	
16-2	Piezoelectric Crystals, 360	
16-3	Voltage-Variable Capacitor Diodes, 369	
16-4	Thermistors, 374	
	<i>Glossary of Important Terms</i> , 379	
	<i>Review Questions</i> , 380	
<b>Chapter 17</b>	<b>INTEGRATED CIRCUITS</b>	<b>383</b>
17-1	Introduction, 383	
17-2	Monolithic, Thin-Film, Thick-Film, and Hybrid Integrated Circuits, 383	
17-3	Fabrication of a Monolithic Integrated Circuit, 386	
17-4	IC Components, 389	
17-5	The Differential Amplifier, 395	
17-6	IC Differential Amplifier, 403	
17-7	Digital Integrated Circuits, 407	
17-8	Integrated Circuit Packaging, 409	
	<i>Glossary of Important Terms</i> , 410	
	<i>Review Questions</i> , 412	
<b>Chapter 18</b>	<b>ELECTRON TUBES</b>	<b>413</b>
18-1	Introduction, 413	
18-2	The Vacuum Diode, 414	
18-3	The Vacuum Triode, 418	
18-4	Triode Characteristics, 419	
18-5	Triode Parameters, 423	
18-6	Common Cathode Circuit, 425	
18-7	ac Analysis of Common Cathode Circuit, 427	
18-8	Common Plate Circuit, 431	
18-9	Common Grid Circuit, 432	
18-10	Triode Biasing Methods, 433	
18-11	The Tetrode Tube, 436	
18-12	The Pentode, 439	
18-13	The Variable-Mu or Remote Cutoff Pentode, 441	
18-14	The Pentagrid Converter, 443	
18-15	The Cathode Ray Tube, 445	
	<i>Glossary of Important Terms</i> , 452	
	<i>Review Questions</i> , 456	
<b>INDEX</b>		<b>460</b>

# **Basic Semiconductor Theory**

## **I-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.

## **I-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

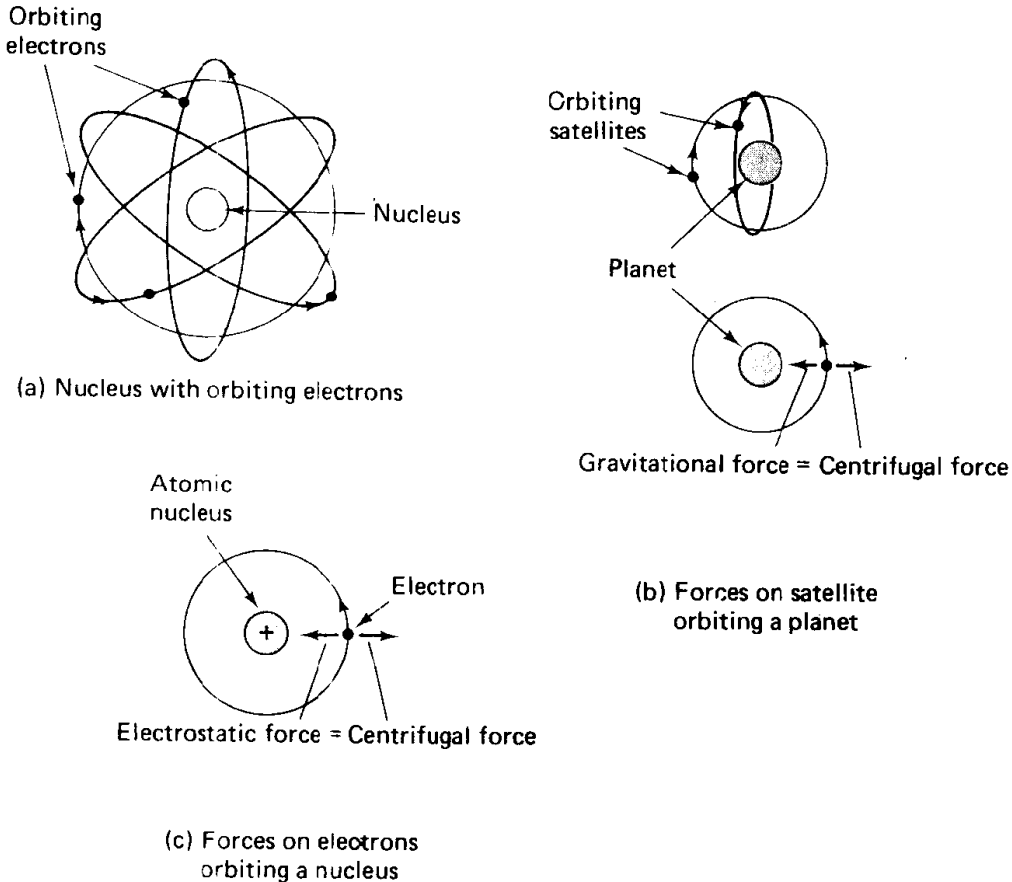
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in orbit around it. Just as satellites are held in orbit by an attractive force of gravity due to the mass of the planet, so each electron is held in orbit by an *electrostatic* force of attraction between it and the nucleus.

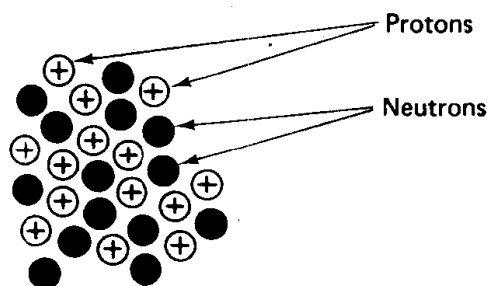
The electrons each have a negative electrical charge of  $1.602 \times 10^{-19}$  coulombs (C), and some particles within the nucleus have a positive charge of the same magnitude. Since opposite charges attract, a force of attraction exists between the oppositely charged electron and nucleus. As in the 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.

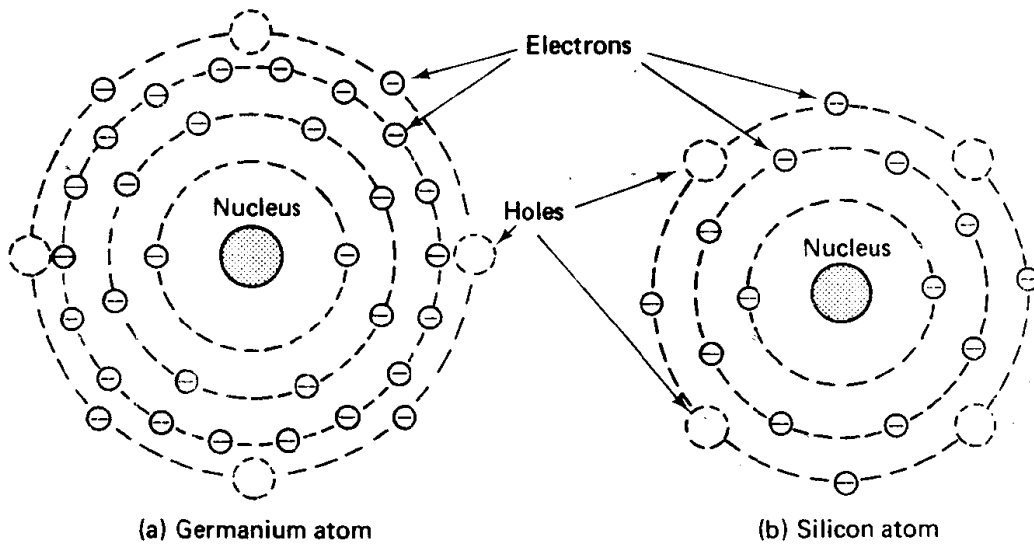
Since the protons and orbital electrons are equal in number and equal and opposite in charge, they neutralize each other electrically. For this reason, all atoms are normally electrically neutral. If an atom loses an electron, it has lost some negative charge. Therefore, it becomes positively charged 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.

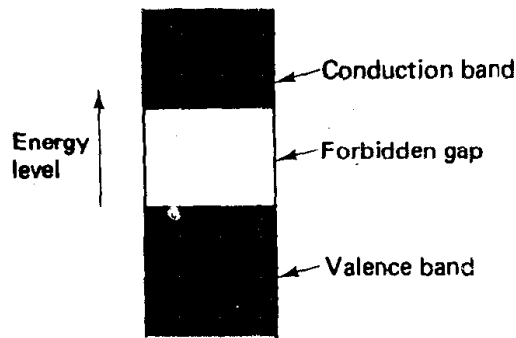
The atoms of two important semiconductors, *silicon* (Si) and *germanium* (Ge), are illustrated in Fig. 1-3. It is seen that each of these atoms has four electrons in a valence shell that can contain a maximum of eight. Thus, we say that their valence shells have four electrons and four *holes*. A *hole* 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.

## I-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



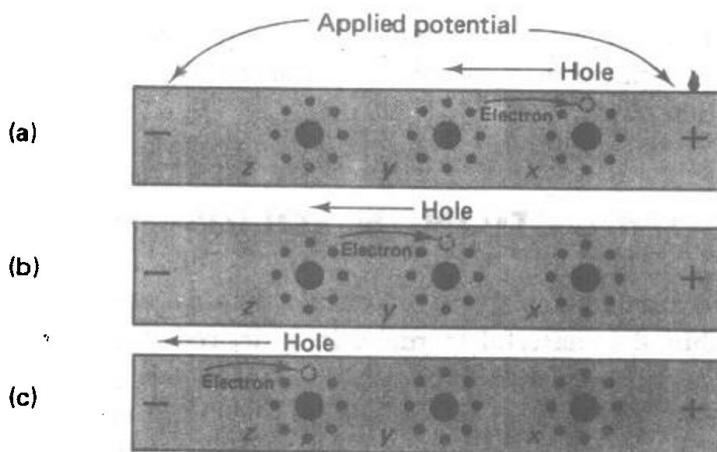
electrons, there are holes where electrons could exist. An electron may jump from one atom to fill the hole in another atom. When it jumps, the electron leaves a hole behind it, and we say that the hole has moved in the opposite direction to the electron. In this way a current flows which may be said 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  $z$ .