

# ELECTRONICS

## Circuits and Devices

RALPH R. WRIGHT

H. RICHARD SKUTT

# ELECTRONICS

## Circuits and Devices

RALPH R. WRIGHT

VIRGINIA POLYTECHNIC INSTITUTE

H. RICHARD SKUTT

VIRGINIA POLYTECHNIC INSTITUTE

THE RONALD PRESS COMPANY

•

NEW YORK

Copyright © 1965 by  
THE RONALD PRESS COMPANY

---

*All Rights Reserved*

No part of this book may be reproduced  
in any form without permission in writing  
from the publisher.

2 V

Library of Congress Catalog Card Number: 65-13463

PRINTED IN THE UNITED STATES OF AMERICA

# Preface

This textbook is designed to be used in a basic course in electronics for students of engineering. It is intentionally broad in scope, since many students will take no more than a one-semester course in electronics. Yet it presents theory in sufficient depth to give the student adequate background for continued study at an advanced level. The material has also been arranged to give the instructor considerable freedom and flexibility in his choice and emphasis of topics.

All electronic devices are discussed prior to considering circuit applications, with separate chapters devoted to semiconductor devices, vacuum tubes, and gas tubes. The theory of semiconductors is comprehensively treated, especially as it applies to such existing devices as junction diodes, transistors, tunnel diodes, Zener diodes, silicon controlled rectifiers, phototransistors, solar cells, and unijunction transistors. However, the treatment is fundamental enough to be applied to the understanding of a host of additional devices now available or under development.

In dealing with circuit applications, discussions of the various devices are completely integrated; major emphasis, however, is given to those devices most commonly used in a given type of circuit. For example, in the chapters dealing with amplification both transistors and vacuum tubes are utilized, with major emphasis on transistor amplifiers. In the discussion of computing circuits, semiconductor devices are used exclusively because of their overwhelming preference over vacuum tubes in this area. Liberal use has been made of illustrations to enhance and facilitate text discussions. Applications of principles are clearly demonstrated by means of numerous illustrative examples.

We wish to express our thanks and appreciation to Dr. Glen Richardson, Worcester Polytechnic Institute, for his valuable suggestions and criticism of the entire manuscript. We thank also our colleagues in the Department of Electrical Engineering at the Virginia Polytechnic Institute for their many helpful suggestions and criticisms of various sections of the manuscript. We wish to mention especially the contributions of Professor B. L. Dennison, whose careful reading, suggestions, and criticism of the entire manuscript were invaluable, and also that of

Dr. C. A. Holt in his helpful criticism of Chapters 2, 5, 6, and 7. Thanks are also due the following for their suggestions during the initial planning stages of the manuscript: Dr. J. Stuart Johnson, Dean of Engineering at Wayne State University; Professor R. T. Nethken, Louisiana State University; Professor G. R. Powley and Dr. H. L. Wood, both of the Virginia Polytechnic Institute; and Mr. R. L. Beaver, General Electric Company. To the many electrical manufacturers who supplied both illustrations and technical information we are most appreciative. And last but not least, a special note of thanks to Mrs. Ralph R. Wright, who despite her many household tasks found time to type the manuscript.

RALPH R. WRIGHT  
H. RICHARD SKUTT

Blacksburg, Virginia  
January, 1965

RALPH R. WRIGHT is Professor of Electrical Engineering at Virginia Polytechnic Institute. He also taught at New York University and has been employed by DuPont, General Electric, IBM, Sandia, Western Electric, and Westinghouse. He is a Registered Professional Engineer and has served as a consultant to a number of companies.

H. RICHARD SKUTT is Associate Professor of Electrical Engineering at Virginia Polytechnic Institute. He served as an electronics officer in the United States Air Force and has been employed by General Electric and the Hughes Aircraft Company.

# Contents

CHAPTER	PAGE
<b>1 Electron Emission</b>	<b>3</b>
Introduction, 3    Electron Emission, 8    Thermionic Emission, 8 Schottky Effect, 11    Photoelectric Emission, 11    Secondary Emission, 14    High-Field Emission, 16	
<b>2 Charged-Particle Ballistics</b>	<b>19</b>
Charged Particles in Electric Fields, 19    Charged Particles in Magnetic Fields, 22    The Cathode-Ray Tube, 25    The Mass Spectrograph, 29    The Linear Accelerator, 31    The Cyclotron, 32	
<b>3 Thermionic High-Vacuum Tubes</b>	<b>38</b>
Basic Structure of Vacuum Tubes, 39    Characteristics of High-Vacuum Diodes, 42    Plate Resistance, 48    Current and Power Relationships, 50    Characteristics of the High-Vacuum Triode, 51    Parameters of the High-Vacuum Triode, 57    Tetrodes, 59    Pentodes, 63    Beam Power Tubes, 67    Multiple-Unit Tubes, 69    Ultra-High-Frequency Tubes, 69    Ceramic Tubes, 73	
<b>4 Gaseous Devices</b>	<b>78</b>
Ionization and Deionization, 79    Thermionic Gas Diodes, 81    Thyratrons, 86    Mercury-Pool Cathode Gas Tubes, 93    Glow-Discharge Tubes, 97    Gas Tubes as Sources of Illumination, 98	
<b>5 Semiconductors</b>	<b>102</b>
Conductors and Insulators, 103    Intrinsic Semiconductors, 104    Valence and Conduction Bands, 107    Extrinsic Semiconductors, 110    Semiconductor Carrier Concentrations, 112    Semiconductor Conductivity, 113    Semiconductor Preparation, 114	
<b>6 Semiconductor Diodes and Transistors</b>	<b>117</b>
Semiconductor Diodes, 117    Forward and Reverse Bias, 120    The Diode Volt-Ampere Relationship, 122    Avalanche Breakdown, 123	

Diode Fabrication Techniques, 124	Junction Transistors, 126	
Transistor Current Relationships, 130	The Early Effect, 133	
The Common-Base Configuration, 134	The Common-Emitter Configuration, 136	
The Common-Collector Configuration, 138	Transistor Fabrication Techniques, 139	
Unijunction Transistors, 140	Silicon Controlled Rectifiers, 142	Tunnel Diodes, 145
<b>7 Graphical Analysis of Transistor and Vacuum-Tube Amplifiers . . .</b>		<b>151</b>
Graphical Analysis of a Common-Emitter Transistor Amplifier, 151	Transistor Biasing Circuits and Operating-Point Stability, 157	
Graphical Analysis of the Common-Cathode Vacuum-Tube Amplifier, 166	Vacuum-Tube Biasing Circuits, 168	
<b>8 Small-Signal Analysis of Transistor and Vacuum-Tube Amplifiers . .</b>		<b>178</b>
Classification of Amplifiers, 179	Small-Signal Parameters, 180	
Analysis of Small-Signal Transistor Amplifiers, 185	Lower and Upper Half-Power Frequencies, 193	
Analysis of Small-Signal Vacuum-Tube Amplifiers, 194	Multistage Transistor Amplifiers, 204	
Multistage Vacuum-Tube Amplifiers, 207		
<b>9 Feedback . . . . .</b>		<b>214</b>
Distortion in Amplifiers, 214	General Feedback Theory, 217	
Feedback in Single-Stage Common-Emitter Transistor Amplifiers, 221	Feedback in Multistage Transistor Amplifiers, 226	
Feedback in Common-Cathode Vacuum-Tube Amplifiers, 228		
<b>10 Power Amplifiers . . . . .</b>		<b>235</b>
Transistor Power Amplifiers, 235	Vacuum-Tube Power Amplifiers, 245	
<b>11 Rectifiers and Power Supplies . . . . .</b>		<b>249</b>
Half-Wave Single-Phase Rectification, 250	Single-Phase Full-Wave Rectifiers, 253	
Polyphase Rectification, 256	Utilization Factor, 261	
Power Rectifier Circuits, 262	Ripple or Smoothing Filters, 265	
Ripple Factor, 265	Effects of Inductance and Capacitance on Rectified Waveforms, 267	
$L$ -Section or Inductor-Input and $\pi$ -Section or Capacitor-Input Filters, 270	Smoothing Factor, 272	
Voltage Multiplication, 274	Regulated Power Supplies, 277	
<b>12 Cathode-Ray Oscilloscopes and Electronic Voltmeters . . . . .</b>		<b>283</b>
Cathode-Ray Tubes with Electrostatic Focusing and Deflection, 284	Cathode-Ray Tubes with Magnetic Focusing and Deflection, 289	
Cathode-Ray Tubes with Electrostatic Focusing and Magnetic Deflection, 292	Comparison of Electrostatic, Magnetic, and	



Electromagnetic Cathode-Ray Tubes, 292 Special Types of Cathode-Ray Tubes, 293 The Cathode-Ray Oscilloscope, 294 Time-Base Generators, 296 Basic Applications of the Cathode-Ray Oscilloscope, 300 Electronic Voltmeters, 312 D-c Vacuum-Tube Voltmeters, 313 A-c Vacuum-Tube Voltmeters, 314

### 13 Photosensitive Devices . . . . . 319

Phototubes, 321 Phototube Circuits, 325 Multiplier Phototubes, 327 Photovoltaic Cells, 330 Photoconductive Cells, 334 Phototransistors, 335

### 14 Wave-Shaping and Computing Circuits . . . . . 340

*RC* Differentiating and Integrating Circuits, 340 *RL* Differentiating and Integrating Circuits, 344 Clipping Circuits, 345 Clamping Circuits, 348 Multivibrators, 352 The Bistable Multivibrator, 352 The Monostable Multivibrator, 359 The Astable Multivibrator, 361 Gate or Logic Circuits, 363 Electronic Computers, 366 Digital Computers, 368 Analog Computers, 369

### 15 Control and Switching Circuits . . . . . 377

Silicon Controlled Rectifiers, 378 The SCR as a Static D-c Switch, 382 The SCR as a Static A-c Switch, 383 Phase-Shift Firing of SCR's, 384 Magnetic Firing of SCR's, 388 Controlled Polyphase Rectifiers, 389 SCR Inverter Circuits, 390 Applications of Unijunction Transistors, 393 Thyatron Switching Circuits, 396 Grid-Controlled Rectifier Circuits, 398

### 16 Oscillation, Modulation, and Detection . . . . . 406

Sinusoidal Oscillation, 406 Amplitude Modulation, 408 Frequency Modulation, 412 Demodulation, 413 The Superheterodyne AM Radio Receiver, 415

## APPENDICES

### A Table of Units in the mks System . . . . . 419

### B Physical Properties of Germanium and Silicon . . . . . 420

### C Device Characteristics . . . . . 421

### D Variation of $z$ Parameters with Temperature, Voltage, and Current. 425

### E The $h$ , $y$ , and $z$ Parameters for a Typical Transistor . . . . . 428

### Index . . . . . 429

# ELECTRONICS

## Circuits and Devices



# 1

## Electron Emission

### 1-1. INTRODUCTION

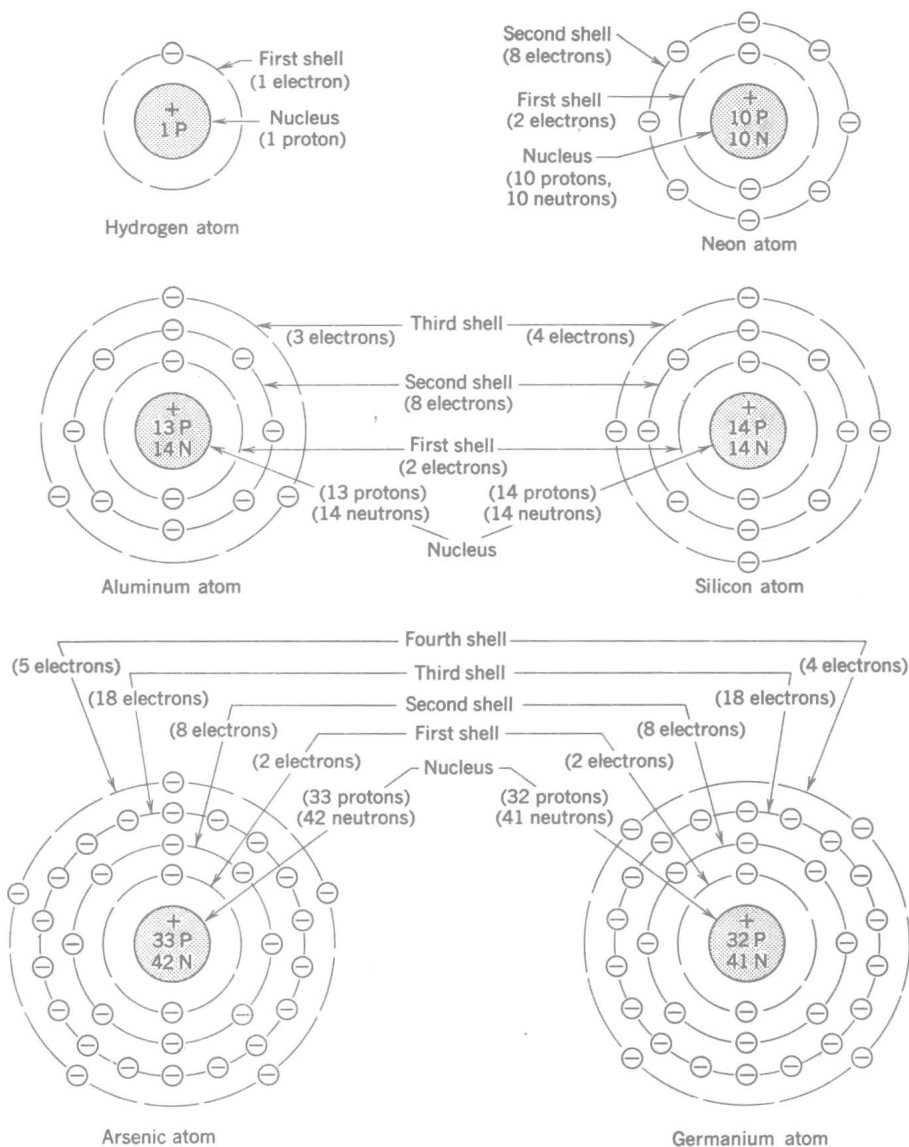
All matter is made up of one or more of the 102 elements that are now known to exist. Of this number, only 92 are found to occur in nature. The fundamental building blocks of all elements are electrons, neutrons, and protons. The characteristics of the various elements are due solely to the number and arrangement of the electrons, neutrons, and protons associated with each atom. The two properties of elements that are of most interest here, chemical and electrical properties, are determined primarily by the outer-shell, or valence, electrons.

Figure 1-1 represents schematically the atomic structure of several elements of particular interest in electronics.

The Bohr model portrays the atom as a nucleus surrounded by electrons, which are established in fixed states or energy levels. There are many more orbits (that is, energy levels) than there are electrons. Therefore, any given atom has many unoccupied states. Furthermore, the electrons are revolving at high velocities in approximately elliptical orbits, somewhat as illustrated in Fig. 1-2. There are three important postulates to the Bohr model:

1. Electrons of any atom can exist only in discrete states and thus possess only discrete amounts of energy corresponding to discrete radii.
2. If an electron effects a transition from a higher energy level to a lower energy level, it radiates a discrete quantity of energy, and if it effects a transition from a lower energy level to a higher energy level, it absorbs a discrete quantity of energy.
3. If an electron maintains a fixed orbit, it neither absorbs nor radiates energy.

In order that an electron may be freed from an atom, it must acquire enough energy to move from its normal orbit,  $r_n$ , to infinity, that is, to such a remote distance from the nucleus that the influence of the atom is negligible. To determine this energy, it is necessary to evaluate the work in transporting an electron from orbit  $r_n$  to infinity. For the



**Fig. 1-1.** Atomic structures, schematically illustrated for several elements.

hydrogen atom,<sup>1</sup> the energy involved may be determined (using Coulomb's law) as follows:

$$F = \frac{e^2}{4\pi\epsilon_0 r^2} \quad (1-1)$$

<sup>1</sup> The hydrogen atom is selected because of simplicity. Because of interaction between electrons, analysis of atoms with two or more electrons involves very complex mathematics, and even then only an approximate solution is possible.

The work done in transporting the electron from  $r_n$  to infinity is

$$\begin{aligned}
 E_p &= \int_{r_n}^{\infty} F \, dr \\
 &= \int_{r_n}^{\infty} \left[ \frac{e^2}{4\pi\epsilon_0} \right] \frac{dr}{r^2} \\
 &= \left[ \frac{e^2}{4\pi\epsilon_0} \right] \left[ \frac{1}{-r} \right]_{r_n}^{\infty} \\
 &= \frac{e^2}{4\pi\epsilon_0 r_n}
 \end{aligned} \tag{1-2}$$

where  $E_p$  = energy required for electron to escape from atom (joules)

$e$  = magnitude of electronic charge (coulombs)

$\epsilon_0$  = permittivity of free space ( $8.85 \times 10^{-12}$  farads/meter)

$r_n$  = normal radius (meters).

Energy  $E_p$  will cause an electron to free itself from the atom and become a free body in space, uninfluenced by the field of the atom. This "escape

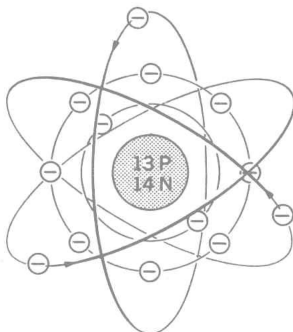


Fig. 1-2. Elliptical orbits of electrons, shown for an aluminum atom.

energy" is somewhat analogous to the energy required to free a projectile from the gravitational field of the earth and thereby become a free body in space.

In the case of a conductor, the electrons in the outer, or valence, shell are not necessarily confined to a given atom and can migrate from one atom to another. Electrons which participate in random migration from one atom to another are known as *free electrons*.

The ratio of charge to mass for the electron was first evaluated in 1897 by Thompson.<sup>2</sup> Present-day data on the electron reveal a mass of approximately  $9.1 \times 10^{-31}$  kg and a charge of approximately  $1.6 \times 10^{-19}$  coulomb. The proton possesses a charge equal and opposite to the charge of the electron and a mass approximately 1836 times as great.

<sup>2</sup> J. J. Thompson, "Cathode Rays," *Annual Report*, Smithsonian Institution, 1897.

On the basis of physical dimensions, the electron is considered to be roughly spherical with a diameter of the order of  $1 \times 10^{-15}$  m, and the diameter of the proton (assuming spherical geometry) is roughly one third of this value.

The neutron has approximately the same mass and physical diameter as the proton. More exact values of various atomic constants are given in Table 1-1.

TABLE 1-1  
Atomic Constants

Constant	Value and Unit
Magnitude of electron charge, $e$	$(1.60206 \pm 0.00003) \times 10^{-19}$ coulomb
Electron rest mass, $m$	$(9.1083 \pm 0.0003) \times 10^{-31}$ kg
Proton rest mass, $m_p$	$(1.67239 \pm 0.00004) \times 10^{-27}$ kg
Neutron rest mass, $m_n$	$(1.67470 \pm 0.00004) \times 10^{-27}$ kg
Specific electron charge, $e/m$	$(1.75890 \pm 0.00002) \times 10^{11}$ coulomb/kg
Velocity of light in vacuum, $c$	$(2.99793 \pm 0.00003) \times 10^8$ m/sec
Planck's constant, $h$	$(6.62517 \pm 0.00023) \times 10^{-34}$ joule-sec
Boltzmann's constant, $k$	$(1.38044 \pm 0.00007) \times 10^{-23}$ joule/°K
Ratio of proton to electron mass, $m_p/m$	$1836.12 \pm 0.02$

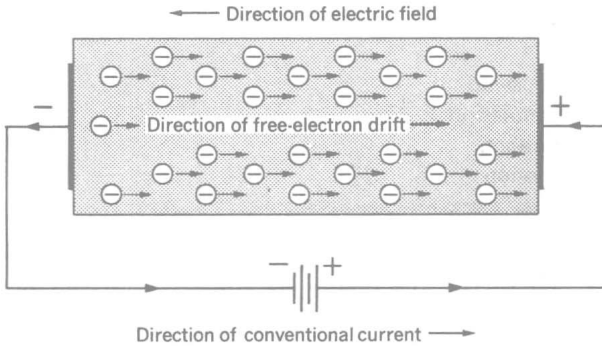
From E. R. Cohen, J. W. M. DuMond, T. W. Layton, and J. S. Rollett, "Analysis of Variance of the 1952 Data on the Atomic Constants and a New Adjustment, 1955," *Reviews of Modern Physics*, Vol. 27 (1955), p. 378.

On the basis of electrical characteristics, all substances may be classified in one of three categories: insulators, semiconductors, or conductors. If the atomic structure of a material is such that outer-orbit electrons are so firmly attached to the nucleus that they cannot move from one atom to another, the material is a perfect insulator. Although there are in practice no such things as perfect insulators, many materials have very low free-electron densities and are therefore good insulators. Examples of insulating materials are glass, porcelain, mica, and polystyrene. Materials which possess high free-electron densities are good conductors. Among the best conductors are silver, copper, and aluminum. Materials with free-electron densities intermediate between conductors and insulators are known as *semiconductors*.

The two semiconducting materials most used in the manufacture of solid-state devices, such as junction diodes and transistors, are germanium and silicon. Although at absolute zero and in the absence of all external excitation pure germanium and silicon are perfect insulators, under normal operating conditions both are semiconductors. Pure silicon possesses a resistivity of the order of 1000 ohm-meters at 25°C, and

pure germanium possesses a resistivity of the order of 0.5 ohm-meter at 25°C. When impurities in controlled amounts are added, as for transistor and solid-state rectifier applications, silicon and germanium exhibit resistivities of the order of 0.001 to 0.10 ohm-meter at 25°C.

The oriented drift of electrons from one atom to another can be achieved by the application of an electric field. Consider the diagram of Fig. 1-3.



**Fig. 1-3.** Drift of free electrons in a conductor, due to an electric field.

The drift velocity of the electrons is proportional to the electric field intensity and is expressed by the relation

$$v = \epsilon \mu \tag{1-3}$$

where  $v$  = drift velocity of electrons (m/sec)

$\epsilon$  = field intensity (volts/m)

$\mu$  = mobility of the electrons (m<sup>2</sup>/volt-sec). This factor is a measure of the ease with which electrons drift in the presence of an electric field.

This drift of charge through the material results in current ( $dq/dt$ ). The current density,  $J$ , is expressed as

$$J = env \tag{1-4}$$

where  $J$  = current density (amp/m<sup>2</sup>)

$e$  = magnitude of electronic charge (coulombs)

$n$  = free-electron concentration (electrons/m<sup>3</sup>).

Substituting  $\epsilon \mu$  for  $v$ ,

$$J = en\epsilon \mu$$

Letting  $\sigma = en\mu$ ,

$$J = \sigma \epsilon \tag{1-5}$$

where  $\sigma$  = conductivity (mhos/m).



## 1-2. ELECTRON EMISSION

Electron emission is defined as "the liberation of electrons from an electrode into surrounding space."<sup>3</sup> Emission might be thought of as the "boiling off" of free electrons from the surface of a metal. There are four means whereby free electrons may acquire sufficient energy to be emitted from a metallic surface, giving rise to four types of emission, namely:

1. Thermionic emission
2. Photoelectric emission
3. Secondary emission
4. High-field emission

Radioactivity is often referred to in the literature as a type of electron emission, because beta (electron) emission is associated with radioactive disintegration. However, the electrons constituting the beta emission are not outer-shell (valence) electrons but are generated in the nucleus. Also, the level of beta emission is so low that it is generally of little practical use. The emission of electrons associated with radioactivity does not properly fall within the category of electron emission (so far as electron tubes are concerned) and will not be treated here.

## 1-3. THERMIONIC EMISSION

The first recorded experiment that gave evidence of thermionic emission was performed by Thomas A. Edison in 1883.<sup>4</sup> While experimenting with the incandescent lamp, Edison discovered that current could be detected in a lead connected between the filament and a positive electrode within the evacuated glass bulb. Although he was unable to explain this phenomenon (later known as the *Edison effect*), he applied for and received a patent on a device based on this effect. It was later established that the current was due to the flow of thermionically emitted electrons from the filament to the positive electrode.

The energy distribution of electrons in metals is described by the Fermi-Dirac distribution, which is illustrated in Fig. 1-4 for four different values of temperature.

The Fermi-Dirac distribution gives the number of electrons,  $dN$ , per unit volume in the energy range  $dE$  at temperature  $T$ . The distribution

<sup>3</sup> IRE (IEEE), *Dictionary of Electronics Terms and Symbols*, New York, 1961, p. 51. In 1963, the Institute of Radio Engineers (IRE) and the American Institute of Electrical Engineers (AIEE) merged to form the Institute of Electrical and Electronics Engineers (IEEE).

<sup>4</sup> E. J. Houston, "Note on Phenomena in Incandescent Lamps," *Trans. AIEE* (IEEE), Vol. 1 (1884), p. 1.