ELECTRONICS

Circuits and Devices

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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.

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Blacksburg, Virginia
January, 1965

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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

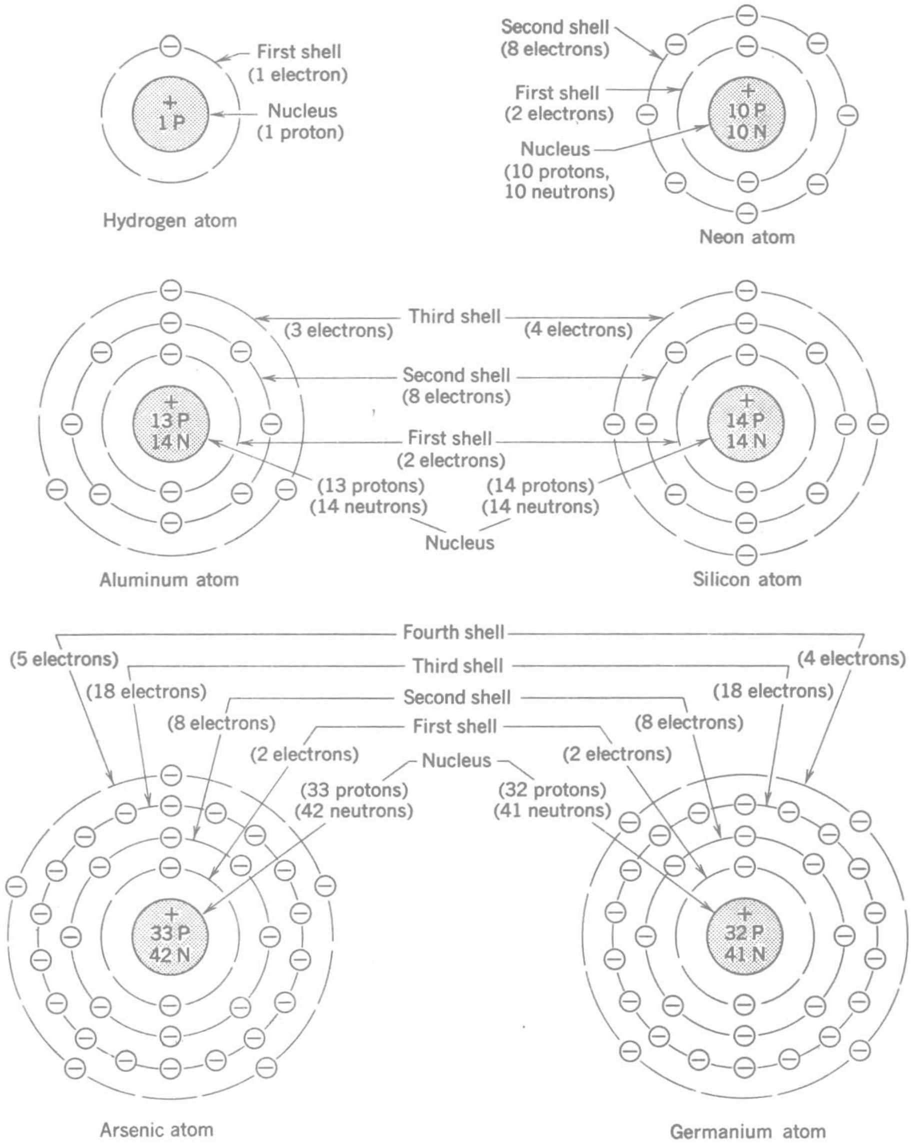

Fig. 1–1. Atomic structures, schematically illustrated for several elements.

hydrogen atom,[1] the energy involved may be determined (using Coulomb's law) as follows:

$$F = \frac{e^2}{4\pi\epsilon_0 r^2} \tag{1–1}$$

[1] 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)
ϵ_0 = permittivity of free space (8.85×10^{-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

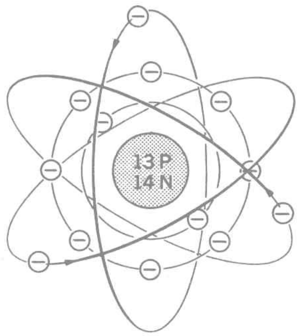

Fig. 1-2. Elliptical orbits of electrons, shown for an aluminum atom.

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.[2] Present-day data on the electron reveal a mass of approximately 9.1×10^{-31} kg and a charge of approximately 1.6×10^{-19} coulomb. The proton possesses a charge equal and opposite to the charge of the electron and a mass approximately 1836 times as great.

[2] 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 1×10^{-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 ± 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.

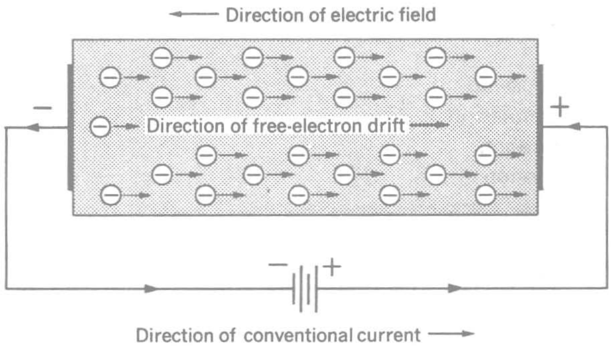

Fig. 1–3. Drift of free electrons in a conductor, due to an electric field.

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

$$v = \mathcal{E}\mu \tag{1–3}$$

where v = drift velocity of electrons (m/sec)
$\mathcal{E}$ = field intensity (volts/m)
μ = mobility of the electrons (m^2/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^2)
e = magnitude of electronic charge (coulombs)
n = free-electron concentration (electrons/m^3).

Substituting $\mathcal{E}\mu$ for v,

$$J = en\mathcal{E}\mu$$

Letting $\sigma = en\mu$,

$$J = \sigma\mathcal{E} \tag{1–5}$$

where σ = conductivity (mhos/m).

1–2. ELECTRON EMISSION

Electron emission is defined as "the liberation of electrons from an electrode into surrounding space."[3] 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.[4] 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

[3] 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).

[4] E. J. Houston, "Note on Phenomena in Incandescent Lamps," *Trans. AIEE* (IEEE), Vol. 1 (1884), p. 1.