Electronics Engineers' Handbook

DONALD G. FINK
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Preface to the Second Edition

Since the first edition of this Handbook was published, the digital revolution has taken full command of electronics engineering. In 1975 digital methods were at the root of the computer and radar industries and were making large inroads into the field of telecommunications. Hardly to be imagined was that the vastly increased density of devices in integrated circuits and their sharply lower costs, then in store, would in less than a decade so extend the range of digital electronics that no aspect of commercial, industrial, or domestic life would remain untouched.

This sweeping change in the methods and outlook of electronics engineering has made a corresponding impression on the content of this new edition. Except for parts dealing with unchanging fundamentals, few sections of the earlier edition escaped the need for revision. The experts who have served as contributors have taken on the task of reviewing, deleting, adding to, and reorganizing their earlier work, particularly to incorporate new digital theory and technology. This occurred even in the section on mathematical formulas, which now includes standard notation and formulas for the Nyquist limits and other aspects of digitized signal transmission.

The earlier analogic systems of electronics have not been quiescent. For example, many startling improvements in video and audio engineering, which still deal primarily with analog signals, are fully covered in this new edition, as are the new arts of transduction and detection and production of radiant energy. Perhaps the majority of applications, once limited to analog signals, are now committed to digital methods, e.g., sound reproduction and television production. The digital filter now permits low-cost operations once prohibitively expensive or practically impossible in lumped-constant or distributed analog designs. This list could be extended indefinitely. Suffice it to say that digital methods have been embraced in this edition in those sections to which they apply as we go to press.

In addition to these revisions of previously published material, three entirely new subjects, dealing primarily with digital methods, have been added to the Handbook. The first is, of course, the microprocessor, on which the pervasive influence of electronics now so largely depends. This subject required the addition of 56 printed pages of material to Section 8, on integrated circuits. That section has also been expanded to include new material on VMOS technology, charge-coupled devices, voltage reference circuits, switching regulators, linear MOS circuits, data-conversion circuits, integrated-circuit filters, integrated injection logic, static and dynamic memory circuits, and logic arrays.

The second new section is on computer-aided design of electronic circuits, Section 27. Third is reliability of electronic components and systems, Section 28. This last is a vital new subject, as the ever increasing number of active elements in a given system puts new demands on the reliability of each one and requires great care in assessing the overall reliability of a system of hundreds of thousands of nominally highly reliable parts, the failure of any one of which might have disastrous results.

Central to the successful extension of digital electronics to many new areas of application are the new arts of telecommunication. Section 22 is a wholly new treatment by 21 members of the technical staff of the Bell Telephone Laboratories and one from the Teletype Corporation. This is the best handbook treatment of the subject yet composed, in my judgment. It is comprehensive, up to date, clearly written, well organized, and, as might be expected, quietly authoritative.

The editor and associate editor are deeply impressed with the competence, balance, and insight the 173 contributors have brought to this new edition, in taking into account one of the most dramatic and rapid periods of change that has occurred in the busy history of electronics. The result is a Handbook of 2,270 printed pages, more than a million words of text, 2,125 illustrations, and 3,285 bibliographic entries. To all those who have faithfully labored to make it possible, we give thanks.

The present Handbook can be considered a companion volume to the "Standard Handbook for Electrical Engineers," the 11th edition of which, under the editorship of the undersigned and H. W. Beaty, is now in print. The Electrical Handbook is devoted primarily to the techniques of electrical power engineering, i.e., "heavy current" generation, distribution, and application. Together the two Handbooks cover the whole field embraced, for example, by the Institute of Electrical and Electronics Engineers. Aside from the different focus of subject matter, the aim of the Electronics Handbook is the same as that of the Electrical Handbook: to contain in a single volume all pertinent data within its scope, to be accurate and comprehensive in technical treatment, to be used in engineering practice (as well as in study in preparation for such practice), and to be oriented toward application, with sufficient theoretical background to assure basic understanding of application requirements. The present Handbook is divided into four major parts: principles employed in electronics engineering (Sections 1 to 5), materials, devices, components and assemblies (Sections 6 to 11), electronic circuits and functions (Sections 12 to 18), and systems and applications (Sections 19 to 28).

The substantial effort made by all the contributors not only to cover their special fields comprehensively but to present their work in the most compact fashion consistent with informed and ready use is gratefully acknowledged. I wish particularly to welcome Associate Editor Donald Christiansen, well known to readers of this Handbook as editor of *IEEE Spectrum*. We look forward to continued collaboration as the art progresses to the point where still another edition is required.

Donald G. Fink
EDITOR-IN-CHIEF

Section 1

Basic Phenomena of Electronics

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CONTENTS

Numbers refer to paragraphs

ELECTRONICS ENGINEERING

1. Electronics. Electronics is the field of science and engineering dealing with the release, transport, control, collection, and energy conversion of subatomic particles having mass and charge (such as electrons) acting in materials with known electromagnetic properties, e.g., vacuum, gases, or semiconductors. The charged particles are called *charge carriers.*

The phenomena of electronics depend upon the number of participating charge carriers, their dynamic activity, and the properties of the environment in which the charges act. The charge carriers are usually electrons, but they may be holes or positive or negative ions. The dynamic activity of charge carriers results from the force and recoverable energy needed to release them from atoms to produce their displacement, velocity, or acceleration in accordance with the principles of relativistic quantum mechanics. The properties of the environment depend upon the composition, structure, and changes in energy levels of atoms composing the substance through which charge carriers (or their fields) pass.

The basic principles of electronics are the same as those of electricity and magnetism. Electricity is any manifestation of energy conversion of charge carriers that initiates or yields forces producing displacement, velocity, or acceleration in the direction of their movement. Magnetism is any manifestation of the kinetic energy of charge carriers arising from or producing forces in a direction perpendicular to their motion. The principles of electronics and electromagnetism are built upon the physical entities of mass, length, time, electric charge (or current), temperature, amount of substance, and luminous intensity. All electromagnetic quantities are now expressed in the SI units (see Par. **1-201**).

The primary differences between electronics and electromagnetism lie in their applications. Compared with the traditional field of electromagnetism, electronics makes possible devices having much greater degree of control over the instantaneous, rather than the average, movement of charges during transport, and the control of charges can be exceedingly rapid. Active electron devices require an external source of power to maintain their electrodes at suitable operating voltages and currents. Electron devices are also, for the most part, nonlinear elements whose output voltages and current are disproportionately related to their input counterparts. At the expense of power from an external supply, many electron devices can provide at their output terminals an amplified version of the voltage, current, or power supplied to their input terminals.

Originally electronics dealt with the conduction of electricity in vacuum or gaseous tubes. Since the invention of the transistor in 1948 conduction through crystalline semiconductors (*solid-state* conduction) has virtually dominated the field, and thermionic electron tubes have played a role of diminishing importance except for applications requiring high power.[1]

2. Electronics Engineering. Electronics engineering is the branch of applied science concerned with active devices and systems, i.e., those requiring external power supply to function properly, in which a dominant role is played by the release, transport, control, collection, and energy conversion of elementary charges. It frequently deals with lower energy levels than electrical engineering does.

Electronics engineering is more closely allied with, and dependent upon, the composition, atomic structure, and mode of electric conduction in composite materials than electrical engineering.

ELECTRONIC PROPERTIES AND STRUCTURE OF MATTER

3. Elementary Particles. The charged elementary particles of principal interest in electronics are the electron and the proton, designated e^- and p^+, respectively. The mass, charge, and charge-to-mass ratios of these particles are as follows:

	Electron	Proton
Mass at rest, kg	9.1096×10^{-31}	1.6726×10^{-27}
Charge, C	-1.6022×10^{-19}	$+1.6022 \times 10^{-19}$
Charge-to-mass ratio, C/kg	1.7588×10^{11}	9.5791×10^{7}

The elementary particles whose existence has been experimentally verified or postulated on theoretical grounds are listed in Table 1-1.

4. Atomic Structure. The atoms of each element consist of a dense nucleus around which electrons travel in well-defined orbits, or shells. The total mass of the nucleons (protons and neutrons) is taken to be equal to the mass of the atom. The number of nuclear protons is equal to the *atomic number* Z of the element. The number of nucleons is equal to the *mass number* A of the atom, and $A - Z$ is the number of neutrons in the nucleus. Heavy atoms have more neutrons than protons; excess of neutrons over protons is important in determining the stability of atoms, i.e., their radioactive properties. Atoms having the same atomic number but different mass numbers have the same chemical properties but different atomic weights. They are called *isotopes* of the chemical element.

The diameter of the atomic nucleus is between 10^{-15} and 10^{-16} m, whereas the diameter of the outer orbiting electrons (the diameter of the atom) is of the order of 10^{-10} m.

The nucleus carries a positive charge equal to the atomic number Z of the element times 1.6×10^{-19} C, the charge of a proton. In the normal (un-ionized) atom there are Z orbiting electrons,

[1]Earlier developments in electron tubes and circuits are covered in the following works, which include extensive references: H. J. Van der Bijl, "Thermionic Vacuum Tube," McGraw-Hill, New York, 1920 (the first comprehensive and authoritative treatment of electron tubes and long a standard reference); E. L. Chaffee, "Theory of Thermionic Vacuum Tubes," McGraw-Hill, New York, 1933 (fundamentals of low-power, negative-grid tubes as amplifiers and detectors; uses nonstandard mathematical notation); H. J. Reich, "Theory and Applications of Electron Tubes," McGraw-Hill, New York, 1939 (physical principles of tubes and associated networks; includes treatment of gaseous devices); M.I.T. Dept. of Electrical Engineering, "Applied Electronics," Wiley, New York, 1943 (undergraduate course in electronics, electron tubes, associated circuits, and practical applications); K. R. Spangenberg, "Vacuum Tubes," McGraw-Hill, New York, 1948 (concerned largely with physical behavior and basic design of tubes; discusses ultra-high-frequency effects, electron bunching, electron optics, and cathode-ray and special tubes); F. A. Maxfield and R. R. Benedict, "Theory of Gaseous Conduction and Electronics," McGraw-Hill, New York, 1941 (fundamentals and applications of gaseous conduction, corona, sparking, glows, and arcs); J. D. Cobine, "Gaseous Conductors," McGraw-Hill, New York, 1941 (theory and applications of electrical discharges in gases); A. Guthrie and R. A. Wakerlin (eds.), "Characteristics of Electrical Discharges in Magnetic Fields," McGraw-Hill, New York, 1949 (Manhattan Project studies on the characteristics of electric discharges in gases and vapors, especially of uranium compounds, in magnetic fields).

Table 1-1. Elementary Particles

Family name	Name of particle	Symbol	Mass ($e^- = 1.0$)	Mass, MeV	Lifetime, s	Spin	Charge ($e^- = -1.0$)	Anti-particle
	Photon	γ	0	0	∞	1	0	γ
Electron	Electron	e^-	1	0.51098	∞	½	−1	e^+
	Electron neutrino	ν_e	0	0	∞	½	0	$\bar{\nu}_e$
Muon	Muon	μ^-	206.768	105.654	2.212×10^{-6}	½	−1	μ^+
	Muon neutrino	ν_μ	. . .	0	∞	½	0	$\bar{\nu}_\mu$
Meson	Pion, positive	π^+	273.18	139.59	2.55×10^{-8}	0	1	π^-
	Neutral	π^0	264.20	135.0	1.9×10^{-16}	0	0	π^0
	Kaon, positive	K^+	966.6	493.9	1.22×10^{-8}	0	1	$\bar{K}^+$
	Neutral	K^0	974.2	497.8	1.0×10^{-10} 6.1×10^{-8}	0	0	$\bar{K}^0$
Baryons	Nucleon, proton	p^+	1,836.12	938.213	∞	½	1	$\bar{p}^+$
	Nucleon, neutron	n^0	1,838.65	939.507	1.013×10^3	½	0	$\bar{n}^0$
	Lambda	Λ^0	2,182.8	1,115.36	2.51×10^{-10}	½	0	$\bar{\Lambda}^0$
	Sigma, positive	Σ^+	2,327.7	1,189.40	8.1×10^{-11}	½	1	$\bar{\Sigma}^+$
	Neutral	Σ^0	2,332	1,191.5	$\sim 10^{-20}$	½	0	$\bar{\Sigma}^0$
	Negative	Σ^-	2,340.5	1,195.6	1.6×10^{-10}	½	−1	$\bar{\Sigma}^-$
	Xi, neutral	Ξ^0	2,566	1,311	1.5×10^{-10}	½	0	$\bar{\Xi}^0$
	Negative	Ξ^-	2,580	1,318	1.28×10^{-10}	½	−1	$\bar{\Xi}^-$

each with negative charge $e^- = -1.6 \times 10^{-19}$ C. At distances large compared with the atomic radius, the atom shows no net electric charge.

The extranuclear (electronic) structure of the atom is characteristic of the element. The orbiting electrons are arranged in successive *shells*. In order of increasing distance from the nucleus these shells are designated *K*, *L*, *M*, *N*, *O*, *P*, and *Q*. The number of electrons each shell can contain is limited. The electrons of the inner shells of complex atoms are tightly bound to the nucleus, and their paths can be altered only by high-energy particles, such as gamma rays. In the more complex atoms, electrons of the outer shells are relatively loosely bound to the nucleus. The outer shells account for the chemical and electrical properties of the elements.

5. Electron Orbits, Shells, and Energy States. Each orbiting electron in an atom has energy which is uniquely characterized by four *quantum numbers*. According to Pauli's exclusion principle, the wave functions describing the electrons must differ by at least one quantum number in the complete set required for their description.

An electron within an atom can be specified in terms of (1) a *principal quantum number n*, (2) an *azimuthal quantum number l*, (3) a *spatial quantum number* m_l, and (4) a *spin quantum number* m_s or *s*. The principal quantum number n specifies the shell in which an electron is located and hence principally specifies the energy state of the electron. Electrons lodged in the *K*, *L*, *M*, *N*, *O*, *P*, and *Q* shells have principal quantum numbers $n = 1, 2, 3, 4, 5, 6$, or 7, respectively.

The azimuthal quantum number l specifies the angular orbital momentum of an electron in each orbital state in various subshells. Together with n, the value of l designates the eccentricity of an electron orbit; the smaller the value of l the greater the eccentricity of the orbits for any given shell. The magnitudes of l may be any integer from 0 to $n - 1$. Electrons whose values of l are 0, 1, 2, 3, 4, and 5, respectively, are referred to as the *s*, *p*, *d*, *g*, and *f* electrons. The number of electrons in a subshell is determined by restrictions on m_l and m_s imposed by Pauli's exclusion principle.

The spatial quantum number m_l specifies differently oriented orbits having the same general shape; it specifies the orientation of the magnetic field of the electron orbit. This quantity is the projection of l on the magnetic axis; it may have $\pm(2l - 1)$ integral values from $-l$ to $+l$ including 0.

The spin quantum number, m_s or s, specifies the direction of spin of an electron on its own axis. Corresponding to spin in opposite directions, the two spin quantum numbers are $+h/2$ and $-h/2$, where $h/2\pi$ is Planck's constant ($= 6.626 \times 10^{-34}$ J·s).

In a normal atom, orbiting electrons are arranged in the set of allowed states having the lowest total energy. As the complexity of atoms increases from hydrogen to uranium (the latter having 92 protons, and 146 neutrons), the electrons fill the shells and subshells by taking those states having the lowest total energy. Sometimes the energy state of an inner shell is less than that of a state in the outermost shell, and this accounts for the fact that some shells may begin to be filled before inner shells are totally filled.

6. Chemical Valence. The chemical properties of the elements are determined by the electrons in the outermost shell (valence electrons). Atoms with completely filled outer shells (the rare gases: helium, argon, krypton, zenon, and radon) are chemically inert. They contain eight electrons in their outer shells.

Atoms with a single electron in the outer shell (lithium, sodium, potassium, rubidium, cesium, franconium, and hydrogen) can easily lose their outer electron. They then become positive ions with completely filled shells.

Atoms with seven outer-shell electrons (the halogens: fluorine, chlorine, bromine, iodine, and astatine) readily pick up an electron from other atoms and become negative ions; they form molecules by sharing electrons and are said to have ionic bonding. Atoms with other numbers of outer-shell electrons tend to unite with other atoms in such ways that each atom has eight outer-shell electrons. Partially filled inner shells have an important bearing on the magnetic properties of the elements.

7. Conduction Electrons. When electrons are in close proximity in crystalline solids, the presence of nearby atoms affects their behavior and their energies are no longer uniquely determined. The single energy level of an electron in a free or isolated atom is thereby spread into a band, or range, of energy levels. Whether or not the band of allowed energies is completely filled with electrons determines its properties as an electric conductor or insulator.

The *conduction band* is a range of states in the free-energy spectrum of a solid in which electrons can move freely; i.e., the electrons must be capable of effecting transitions between energy states. The valence electrons in metals, for example, are not firmly attached to individual atoms but are free to travel within the crystal lattice. Such electrons are called *conduction electrons.* There is one such conduction electron per atom in silver, copper, gold, and the alkali metals, all of which are good conductors.

An insulator or dielectric is a material in which every energy level is filled and the electrons are unable to effect the transitions between states required for electric conduction.

8. Chemical Bonds and Compound Formation. Chemical bonds occur when the total energy of an aggregate is less with atoms near each other than separated. The charges of the atom play an important role in bonding, especially electrons in the outer shells.

Electrostatic or *ionic bonds* result from attractive forces between positive and negative ions or between pairs of oppositely charge ions. *Covalent bonds* occur when atoms share two or more electrons; i.e., shared electrons are attracted simultaneously to two atoms, and the resulting energy stability produces the bond. *Metallic bonds* are those in which the attractive forces result from the exchange interaction of the electron gas with the ionic lattice. *Van der Waals bonds* occur when molecules are formed, giving each atom an outer shell of eight atoms, as in an inert gas.

9. Energy Conversion. Energy in a system can be neither created nor destroyed (except in nuclear processes when energy is converted into its equivalent form, mass). However, one form of energy can be converted into other forms. Thus, the potential energy of a system can be converted into kinetic energy and vice versa, and the energy of particles of one kind can be converted into energy of particles of quite another kind. Heat, produced by the random motion of elementary particles and their aggregates, is the form of energy into which other forms are ultimately converted.

10. Energy Conservation and Mass Equivalence. According to classical physics, energy can be neither created nor destroyed; similarly, mass can be neither created nor destroyed. Relativistic physics identifies mass and energy according to the equation for total energy

$$mc^2 = m_0c^2 + U_k$$

where m_0c^2 is the rest energy of a body or particle and U_k is its kinetic energy. Hence the two conservation laws stated above become one and the same physical law.

11. Electromagnetic Effects. The dynamic behavior of elementary particles possessing both mass and charge produces electromagnetic phenomena. In free space the effects depend only on the nature and distribution of the charges and their motions, but such effects are greatly modified by atomic and molecular structure when charges move in material substances. Thus, the properties of materials modify the effects observed in free space.

The three major classes of electromagnetic materials are *conductors* or *semiconductors*, through which charges can flow more or less readily; *dielectrics* or *insulators*, through which charges are prevented from flowing; and *magnetic materials*, in which the motion of charges produces enhanced transverse forces.

12. Conduction Effects (see Par. **1-62**). Electric conduction is the effect produced in a substance or system having mobile charges by the application of an electric force such that the charged particles flow through the conductor in the direction of the applied force. The phenomenon is attributed to electrons in the outer shells of atoms that are so loosely bound that they can be released by small electric forces. In good conductors free electrons can also be released by chemical, thermal, or other kinds of forces.

13. Dielectric Phenomena. Displacement of electric charges occurs in a substance or system having bound charges. The application of an electric force produces a directed motion of charged particles in the direction of the applied force but of such limited extent that the charges do not separate from their parent atoms (see Par. **1-64**).

Dielectric phenomena are attributed to electrons in the outer shells of atoms which are so tightly bound that they cannot become mobile except through application of electric forces strong enough to destroy the dielectric properties of the material.

Under ordinary conditions, the electric flux density D in a dielectric is proportional to the electric field intensity E acting across the dielectric. But at very high frequencies, hysteresis effects occur in dielectric materials. The phenomenon is similar to that produced in magnetic materials at much lower frequencies (see Par. **1-118**). Hysteresis produces heat losses in dielectrics, just as heat losses occur in magnetic materials displaying hysteresis phenomena.

14. Magnetic Phenomena (see Pars. **1-81** to **1-118**). Magnetic phenomena include a number of effects of substances or systems in which the motions of charged particles set up forces transverse to the motion of charges.

The phenomena are attributed to the electric fields carried by moving charges. Any directed