CHAPTER 1

INTRODUCTION

Electricity is one of the most important parts of modern everyday life. It is used to run product machinery, transportation, communications, medical procedures, military operations, research, and so on. Most of the principles that explain electricity as a form of energy have been known since the 19th century. Scientists like Faraday, Ampère, and Maxwell did most of the fundamental work. Since then, every decade has brought some refinements, new discoveries, and new applications. Polymers (i.e., plastics and elastomers) are very essential materials in electrical applications.

The first known use of a polymeric substance (a natural one at that) as insulation of the first Transatlantic telephone cable was gutta-percha (*trans*-polyisoprene) in the 1860s. Natural rubber (*cis*-polyisoprene) (NR) became a very important insulation material after the invention of vulcanization in the late 1840s.

With the development of synthetic polymers, the selection of insulating materials has been steadily growing (Table 1.1). Today, there are dozens of polymers serving as insulators at extremely low and high temperatures, at a wide range of frequencies, in adverse environments. There are special polymers or their compounds that are conductors or semiconductors and exhibit other specialized properties.

Polymers for Electricity and Electronics: Materials, Properties, and Applications,
First Edition. Jiri George Drobny.

TABLE 1.1 Milestones in the Development of Synthetic Polymers for Electrical and Electronic Applications[a]

Year/Years	Polymer
1907	Phenolic resin
1926	Aniline–formaldehyde resins
1928	Urea–formaldehyde resins
1929	Styrene–butadiene rubber (SBR)
1930	Nitrile–butadiene rubber (NBR)
1931	Polychloroprene rubber (Neoprene)
1937	Butyl rubber (IIR)
	Polyurethanes
1938	Epoxy resins
	PTFE (Teflon)
	Poly(vinyl chloride) (PVC)
	Polyethylene (PE)
1940	Polyamide (Nylon)
1944	Silicones
1950	Linear polyethylene
1951	Chlorosulfonated PE (Hypalon)
1950s (late)	Ethylene–propylene rubbers (EPM, EPDM) elastomers
	Fluorocarbon elastomers (Kel-F)
1964	Carbon (graphite) fibers
1960s (late)	Styrenic block copolymers (Kraton)
	Polyvinylidene fluoride (PVDF)
	Ethylene–tetrafluoroethylene copolymer (ETFE)
	Fluorinated ethylene propylene (FEP)
	Tetrafluoroethylene–perfluoroalkyl vinyl ether copolymer (PFA)
1970s (late)	Conductive polymers
	Polyamide-based thermoplastic elastomers (Pebax)
	Copolyesters (Hytrel)
	Thermoplastic vulcanizates (TPV, Santoprene),
1980s	Thermoplastic polyolefins (TPO)
	Polyaniline
	Iodine-doped polyaniline (2000 Nobel Prize)
1990s to early 2000s	Conducting electroactive polymers (CEPs), including polypyrrole, polythiophene, sulfonated polyaniline
	Organic (polymeric) light-emitting diodes (OLEDs)
2001 to date	Organic (polymer) solar cells

[a] Due to the current multitude of projects involving new products and technologies, it is difficult to show exact years for the individual items.

1.1 ELECTRIC CHARGE

Elementary quantity of charge is $\pm 1\,\mathrm{e}$, with the electron carrying a charge of $-1\,\mathrm{e}$ and the proton $+1\,\mathrm{e}$. The unit of charge is 1 C (coulomb); in some cases this unit is extremely large. A more practical unit is the microcoulomb (μC), which is one millionth of a coulomb. The magnitude of the electron charge is 1.6021×10^{-19} C or 1.6021×10^{-13} μC.

1.1.1 Static Electricity

Static electricity refers to the build up of electric charge on the surface of objects. The static charges remain on an object until they either bleed off to ground or are quickly neutralized by a discharge. Although charge exchange can happen whenever any two surfaces come into contact and separate, a static charge only remains when at least one of the surfaces has a high resistance to electrical flow (as an electrical insulator). The effects of static electricity are familiar to most people because we can feel, hear, and even see the spark as the excess charge is neutralized when brought close to a large electrical conductor (e.g., a path to the ground), or a region with an excess charge of the opposite polarity (positive or negative). The familiar phenomenon of a static "shock" is caused by the neutralization of charge.

Electric charge is an intrinsic characteristic of the fundamental particles making up those objects; that is, it is a characteristic that automatically accompanies those particles wherever they exist. Essentially, many objects contain equal amounts of two kinds of charge: *positive* and *negative* charge and they are said to be *electrically neutral*. If the two types of charge are not in balance, then there is a net charge either positive or negative. Charged objects interact by exerting forces on one another. Charges with the same electrical sign repel each other, while charges with opposite sign attract each other.

The attraction and repulsion between charged bodies have many industrial applications, including electrostatic paint spraying and powder coating, fly-ash collection in chimneys, nonimpact inkjet printing, and photocopying.

1.1.2 Electric Fields

When forces exist at a distance, it is said that force field exists in space. In this case, the force field is referred to as the *electric* or *E field*. This

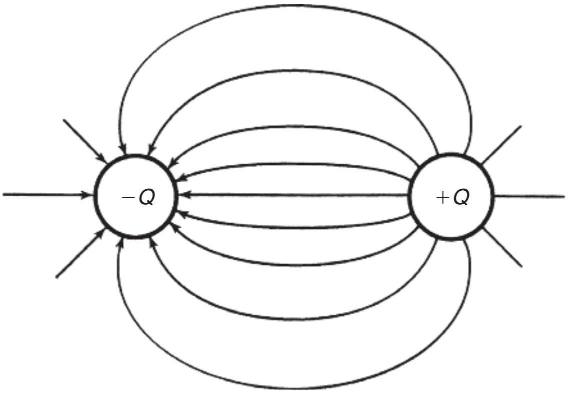

FIGURE 1.1 Electric field between oppositely charged objects. (Ku, C.C. and Liepins, R., *Electrical Properties of Polymers: Chemical Principles,* Hanser Publishers, Munich, 1987, p. 107)

field is represented by field lines represented by lines drawn between the charged objects. These symbolic lines connect units of positive charge (the absence of electrons) with units of negative charge. When more charges are involved, convention says that there are more lines (see Fig. 1.1). The *E* field exists through entire space; the lines are only representation. At every point in space, the force has a magnitude and direction (i.e., it is a *vector*).

1.1.3 The Triboelectric Effect

The *triboelectric effect* (also known as *triboelectric charging*) is a type of contact electrification in which certain materials become electrically charged after they come into contact with another different material and are then separated (e.g., through rubbing). The polarity and strength of the charges produced differ according to the materials, surface roughness, temperature, strain, and other properties.

Thus, it is not very predictable, and only broad generalizations can be made. Amber, for example, can acquire an electric charge by contact and separation (or friction) with a material like wool. This property, first recorded by Thales of Miletus, suggested the word “electricity” (from William Gilbert’s initial coinage, “electra”), from the Greek word for amber, *ēlektron*. Other examples of materials that can acquire a significant charge when rubbed together include glass rubbed with silk, and hard rubber rubbed with fur.

TABLE 1.2 Triboelectric Series

Material	Polarity
	Positive
Silicone elastomer with silica filler	↑
Borosilicate glass, fire polished	
Window glass	
Aniline–formaldehyde resin (acid catalyzed)	
Polyformaldehyde	
Poly(methyl methacrylate)	
Ethyl cellulose	
Polyamide 11	
Polyamide 66	
Rock salt (NaCl)	
Melamine–formaldehyde resin	
Wool, knitted	
Silica, fire polished	
Silk, woven	
Poly(ethylene glycol succinate)	
Cellulose acetate	
Poly(ethylene glycol adipate)	
Poly(diallyl phthalate)	
Cellulose (regenerated) sponge	
Cotton, woven	
Polyurethane elastomer	
Styrene–acrylonitrile copolymer	
Styrene–butadiene copolymer	
Polystyrene	
Polyisobutylene	
Polyurethane flexible sponge	
Borosilicate glass, ground surface	
Poly(ethylene glycol terephtalate)	
Polyvinylbutyral	
Formaldehyde–phenol hardened epoxy resin	
Polychlorobutadiene	
Butadiene–acrylonitrile copolymer	
Natural rubber	
Polyacrylonitrile	
Sulfur	
Polyethylene	
Poly(diphenylol propane carbonate)	
Chlorinated polyether	
Poly(vinyl chloride plasticized with 25% dioctyl phthalate	
Poly(vinyl chloride) without plasticizer	
Poly(trifluorochloroethylene)	↓
Polytetrafluoroethylene	Negative

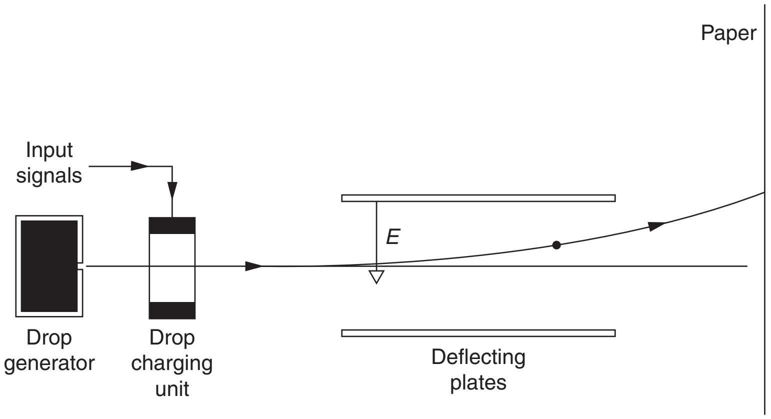

FIGURE 1.2 Essential features of the ink-jet printer. (Halliday, D., Resnick, R. and Walker, J., *Fundamental of Physics Extended, Fifth Edition,* John Wiley & Sons, New York, 1997, p. 547)

Materials are often listed in order of the polarity of charge separation when they are touched with another object in so-called *triboelectric series* (see Table 1.2). A material toward the bottom of the series, when touched to a material near the top of the series, will attain a more negative charge, and vice versa. The further away two materials are from each other on the series, the greater the charge transferred. Materials near each other on the series may not exchange any charge, or may exchange the opposite of what is implied by the list. This depends more on the presence of rubbing, the presence of contaminants or oxides, or upon properties other than on the type of material. Lists vary somewhat as to the exact order of some materials, since the charge also varies for nearby materials.

The phenomenon of acquiring charge through contact accounts for the attraction of dust particles by plastic items, the accumulation of electric charge in carpets in dry weather, and radio frequency (rf) and electromagnetic interference effects of plastics enclosures. One well-established application of this principle is ink-jet printing; the principle is shown in Fig. 1.2. In this application, an input signal from a computer controls the charge given to each drop and thus the position on the paper at which it lands. The accumulation of charge is also a key component in all *xerographic* processes.

1.2 COULOMB'S LAW

Coulomb's law expresses the interaction force between two charges at rest. It is valid for point charges only. This force is

$$F = \left[\frac{1}{4\pi\varepsilon_o}\frac{q_1 q_2}{r^2}\right]\boldsymbol{I}_r \tag{1.1}$$

where q_1, q_2 = magnitude of point charges (+ or −); r = distance between charges; $\boldsymbol{I}_r$ = unit vector along r; and ε_o = permittivity constant ($= 8.85 \times 10^{-12}\,\mathrm{C}^2\,\mathrm{N}^{-1}\cdot\mathrm{m}^{-2}$). The force of attraction or repulsion between point charges at rest acts along the line joining the charges.

1.3 CONDUCTORS AND INSULATORS

Insulators or nonconductors (or dielectrics) are materials containing essentially no charges that are free to move. If such a material is subjected to an electric field, each electron and nucleus within the material experiences a force due to the electric field. However, these charges are bound tightly within the material and are not free to move under this force. Thus the external field does not cause charges to flow in the material, and therefore these materials do not conduct electric charges. Examples here are glass, ceramics, and polyethylene.

A conductor is an opposite of an insulator. In conductors, electrons exist that are free to move through the material. When an electric field is impressed upon such a material, the charges move to produce a current under the action of the field.

This classification is not sharply defined, however. There are materials that contain some charges that can move under the action of the field. If the proportion is significant, these are referred to as *semiconductors*.

1.4 CAPACITORS

Capacitors are devices capable of storing charge and there are several possible arrangements, the most common being parallel conductive plates or concentric cylinders or other shapes (see Fig. 1.3). The principle of a capacitor with parallel conducting plates is shown in Fig. 1.4.

The capability of storing charge is called capacitance, C, and is expressed as:

$$C = \frac{q}{V} \tag{1.2}$$

where q = charge in coulombs (C) and V = potential difference in volts (V).

The unit of capacitance is 1 farad, $1\,\mathrm{F} = 1\mathrm{CV}^{-1}$, but two practical units, 1 microfarad (1 μF) and 1 picofarad (1 pF) are much smaller;

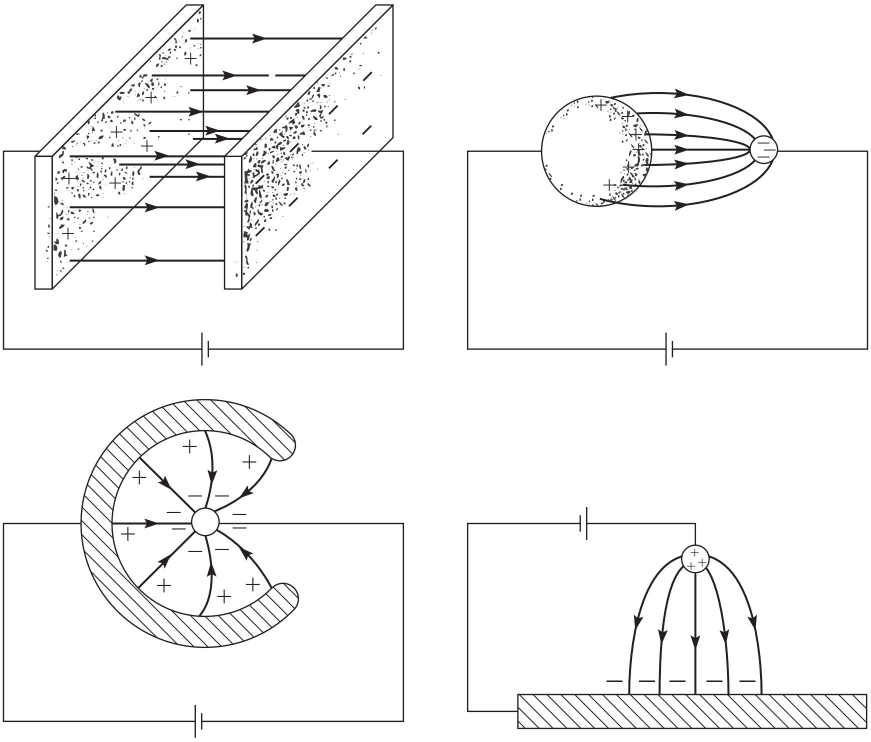

FIGURE 1.3 Examples of devices having capacitance.

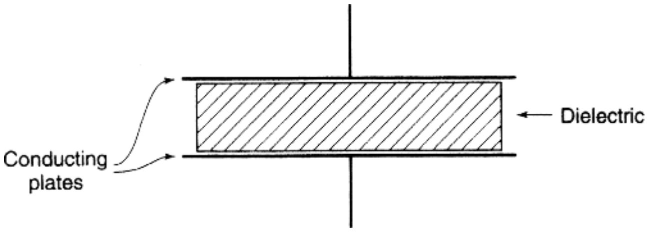

FIGURE 1.4 Principle of a capacitor with parallel conducting plates and a dielectric.

$1\,\mu\text{F} = 10^{-6}\,\text{F}$, $1\,\text{pF} = 10^{-12}\,\text{F}$. One farad of capacitance means that a charge of 1 coulomb can be stored for one volt of potential difference.

1.5 DIELECTRICS AND CAPACITANCE

Dielectrics (nonconducting materials) affect the capacitance of a capacitor. This factor is called a dielectric constant ε and is defined as:

$$\varepsilon = \frac{C}{C_0} \tag{1.3}$$

where C_0 = the capacitance of the capacitor in a vacuum and C = the capacitance with a dielectric between the plates.

The capacitance of a condenser measures the extent to which it is able to store charge. For a nonpolar material the increase in capacitance is due to the charges on the capacitor polarizing the molecules (attracting the positive charges in the molecules to one end and the negative charges to the other) with the result that increased charge appears on the surface, as shown in Fig. 1.5. When the insulating sheet is inserted between the metal plates the voltmeter reading drops from V_0 to V as shown in

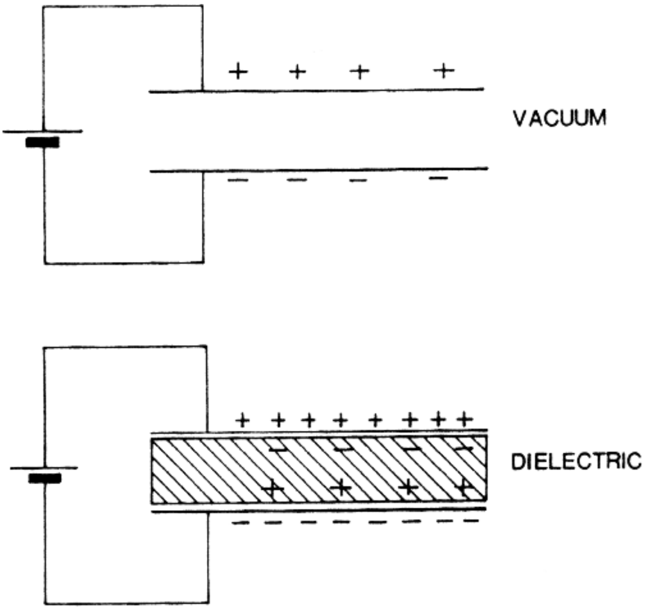

FIGURE 1.5 Surface charge on a condenser.

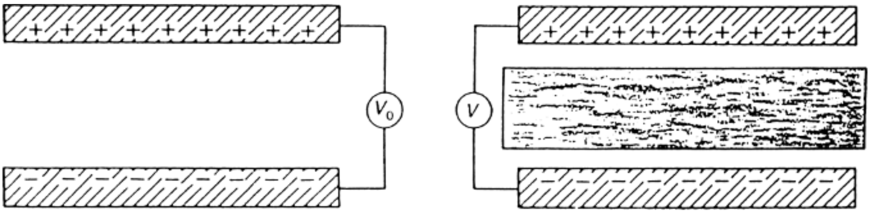

FIGURE 1.6 Effect of an insulator on voltage reading.

Fig. 1.6. Physical meaning of the dielectric constant is that the induced charge decreases the potential between the plates thus increasing the capacitance of the system. The value of dielectric constant alone addresses how an insulator stores the electrical energy so as to isolate electrical elements from each other and the ground. In other words, the higher the value of the dielectric constant, the more charge is stored on the plates for a given voltage. By definition the value of the dielectric constant of air is 1.0. Values of dielectric constants of some materials are in Table 1.3.

The electric potential energy of a charged capacitor, U, is given by

$$U = \frac{q}{2C} = \frac{1}{2}CV^2 \tag{1.4}$$

It is the work required to charge it. This energy can be associated with the capacitor's electric field, E. In vacuum, the *energy density u* or potential per unit volume, is given by

$$u = \frac{1}{2}\varepsilon_0 \cdot E^2 \tag{1.5}$$

TABLE 1.3 Values of Dielectric Constants of Some Materials (From Halliday, D., Resnick, R., and Walker, J., *Fundamentals of Physics Extended, 5th ed.*, John Wiley & Sons, Inc., New York, 1997, p. 639. With permission of John Wiley & Sons.)

Material	Dielectric Constant
Vacuum	1.00000
Air (1 atm)	1.00054
Polystyrene	2.6
Paper	3.5
Transformer oil	4.5
Pyrex	4.7
Ruby mica	5.4
Porcelain	6.5
Silicon	12
Germanium	16
Ethanol	25
Water (20°C)	80.4
Water (25°C)[a]	78.5
Titania ceramic	130
Strontium titanate	310

[a] All other measurements done at 20°C.

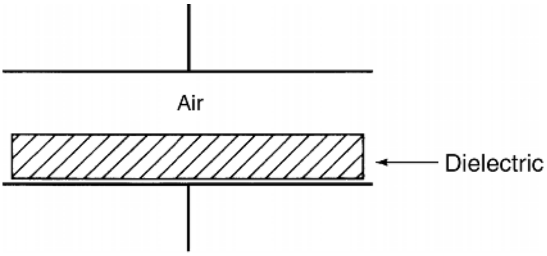

FIGURE 1.7 Air and dielectric between parallel plates. (Ku, C.C. and Liepins, R., *Electrical Properties of Polymers: Chemical Principles,* Hanser Publishers, Munich, 1987, p. 25)

If a dielectric occupies part of the space between the two parallel conducting plates (as shown in Fig. 1.7) the equipotential surfaces are no longer uniformly spaced across the space. Most of the potential difference appears across the air space. The ratio of the E field in the air to the field in the dielectric is the relative dielectric constant ε_r. It is convenient to consider a new field, one that is not dependent on the dielectric. This field is called the *displacement* or D field. This D field is generated by charges and is not a function of the dielectric. To make the units turn out correctly, the D field in air is the E field times the dielectric constant of free space. This constant ε_0 is also known as the *permittivity of free space*. This constant has the value 8.854×10^{-12}. The D field has units of charge per unit area (C m^{-2}). At the interface between the air and the dielectric, the D field has the same intensity on both sides of the interface. The energy stored in a field is proportional to the E, not the D field. In the system shown in Fig. 1.7, most of the energy is stored in the air space in contrast to a system without the air space. When the dielectric is introduced to an existing uniform E field, the field reconfigures itself to store the least possible energy [1].

Another effect of the introduction of a dielectric is to limit the potential difference that can be applied between the plates to a certain value V_{max}, called the *breakdown potential.* If the value is substantially exceeded, the dielectric material will break down and form a conducting path between the plates. Every dielectric material has a characteristic *dielectric strength*, which is the maximum value of the electric field that it can tolerate without breakdown. The values of the dielectric strength of several dielectrics measured at room temperature are in Table 1.4.

TABLE 1.4 Dielectric Strength Values of Selected Dielectrics at Room Temperature

Substance	Dielectric Strength (MV m^{-1})
Air	3
Alumina	13
Window glass	10–14
Pyrex	14
Silicone oil, mineral oil	10–15
Polyethylene	19–22
Polystyrene	16–24
Polyamide 66	14
Polychloroprene rubber	16–28
Paper	16
Bakelite	24
Ultrapure water	30
Waxed paper	40–60
Fused silica	25–40
Mica	20–70
PTFE	60

1.6 DIELECTRIC POLARIZABILITY

If an atom is placed into an electric field, the positive nucleus experiences a force in the direction of the field, while the negative electron cloud is pulled in the opposite direction. As a result, the centers of the positive and negative charge in the atom are separated. Now the atom has become polarized and acts as a dipole. The same is true about a molecule.

Evidently, the greater the polarizability of the dielectric, the higher the dielectric constant. The polarizability *of nonpolar* molecules arises from two effects: (1) *Electronic polarization*, in which the applied electric field causes a displacement of the electrons relative to the nucleus in each atom. (2) *Atomic polarization*, in which the applied field causes a displacement of the atomic nuclei relative to one another. In polar molecules, a third process contributes to the total polarizability: (3) *Orientation polarization*, in which the applied field causes a net orientation of the dipoles to the field.

A *polar* molecule has a permanent dielectric dipole moment; that is, although the molecule is electrically neutral, a distribution charge exists such that the centers of positive and negative charge are separated by a distance of molecular dimensions [2]. The dipole moment, which is equal to charge times distance, is measured in coulomb-meter (Cm). The old electrostatic debye unit of molecular dipoles (D) was equivalent to 3.335×10^{-30} Cm [3]. The overall polarizability of a molecule, α_T,

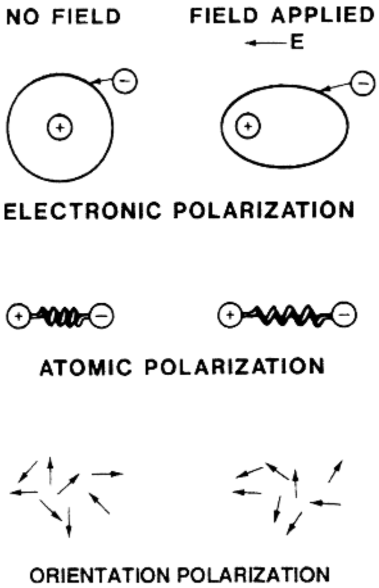

FIGURE 1.8 Mechanisms of polarization.

is the sum of three terms: $\alpha_T = \alpha_e + \alpha_a + \alpha_o$, where α_e, α_a, and α_o are the electronic atomic, and orientation polarizations, respectively [2]. The mechanisms of the above types of polarization are depicted by Fig. 1.8. Molecular dipole moments are listed in Table 1.5 and group dipole moments are in Table 1.6.

If an external electric field is present, the molecular dipoles experience a torque because of it. The torque tends to align the dipoles with the field in such a way that the positive end is moved forward in the direction of the field and the negative end is displaced in a direction antiparallel to it (see Fig. 1.9). If the electric field is alternating, the dipoles will rotate to adjust their positions accordingly. The process generates thermal energy and is the basis of microwave heating.

The correlation of polarizability α with dielectric constant ε is expressed by the Clausius–Mossotti equation:

$$\frac{N\alpha}{3\varepsilon_0} = \frac{\varepsilon - 1}{\varepsilon + 2} \tag{1.6}$$

where ε_0 is the dielectric constant (permittivity of the vacuum) and N is the number density (number of atoms or molecules per volume). The dielectric constant (relative permittivity) is a bulk (macroscopic) property and polarizability is a microscopic property of matter, thus the

TABLE 1.5 Molecular Dipole Moments

Compound	Dipole Moment (10^{-30} Cm)
H_2O	6.1
HF	6.4
HCl	3.6
HBr	2.6
CH_4	0
CCl_4	0
CO_2	0
NH_3	4.9
CH_3Cl	6.2
CH_2C_{12}	5.4
$CHCl_3$	4.0
CH_3F	6.0
C_2H_5OH	5.7
$(C_2H_5)_2O$	3.8
$C_6H_5CH_3$	1.2
C_6H_5Br	5.8
$C_6H_5NO_2$	13.1
$C_6H_4(CH_3)NO_2$ (*para*)	14.6
C_6H_5OH	5.1
$C_6H_4(CH_3)OH$ (*para*)	5.2

TABLE 1.6 Group Dipole Moments

Group	Aromatic Compounds, Moment (10^{-10} Cm)	Aliphatic Compounds, Moment (10^{-30} Cm)
$-CH_3$	1.3	0
Cl	5.3	6.3
–F	5.7	6.0
–Br	5.7	6.7
–I	5.7	6.3
–OH	4.7	5.7
$-NH_2$	5.0	12.3
$-NO_2$	8.5	7.7
$-CF_3$	5.3	13.4
$-CCl_3$	6.8	5.2
–CN	13.5	11.6
–CHO	9.9	8.3
$-OCH_3$	4.3	4.3
–COOH	6.1	5.4
$-COOCH_3$	6.1	6.0
$-COOC_2H_5$	6.3	6.0

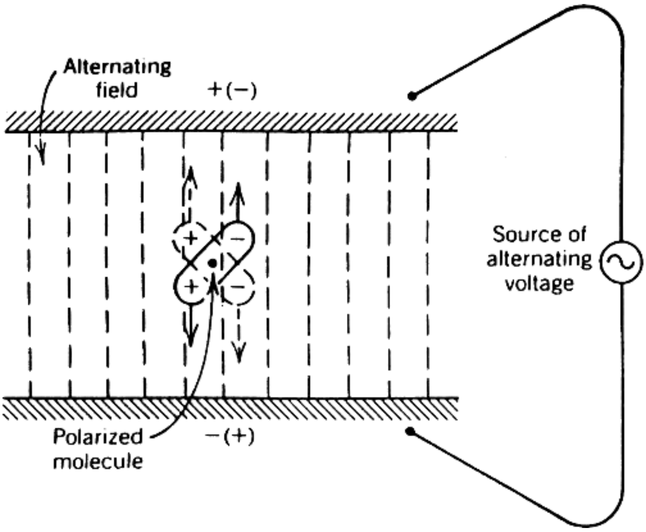

FIGURE 1.9 A molecular dipole immersed in a high frequency field.

relation bridges the gap between a directly observable macroscopic property and a microscopic molecular property.

The equation may be also written in terms of molecular weight M_w and density ρ:

$$\frac{N_A\alpha}{3\varepsilon_0} = \frac{\varepsilon - 1}{\varepsilon + 2}\frac{M_w}{\rho} \tag{1.7}$$

where N_A is Avogadro's number. The quantity $N_A\alpha/3\varepsilon_0$ is called the *molar polarization* P_M and has the dimension of volume. As long as the theory leading to the equation remains valid, the molar polarization remains constant for a particular material irrespective of the temperature and pressure [4]. From the relationship between ε and α it is clear that the way to reduce ε is to lower α and to increase ε is to raise α. Note also that the Clausius–Mossotti equation applies only to nonpolar or weakly polar dielectrics.

1.7 VOLTAGE

The fundamental definition of voltage relates to the work required to move a unit of charge between two points. By definition, the unit of charge is positive. The amount of work does not require a reference level. The work required is measured by the potential difference. It is correct to say that the work per unit charge is the voltage difference. Thus the words *voltage* and *potential* are used interchangeably. The unit of voltage is a volt (V). Large voltages are expressed in kilovolt or 10^3 V (kV), megavolt, 10^6 V (MV), smaller ones are millivolt, 10^{-3} V (mV), and microvolt, 10^{-6} V (μV).

Any point can be selected as zero potential. If a remote point is selected, work might be required to get the given charge to the first body. If this work is 10 V, then the work to get to the second body may be 5 more volts. The potential difference between the two bodies is 5 V. When the charge is positive and the charge transferred is also positive, positive work is done in moving this charge. The work is actually stored in the electric field.

1.8 ELECTRIC CURRENTS

Electric current is the charge passing through a given cross section of the conductor (wire) per unit time. Electrons are carriers of the charge. If charge dq passes through a hypothetical plane in time dt, then the current through that plane is

$$i = \frac{dq}{dt} \tag{1.8}$$

The SI unit for current is the ampere (A):

$$1 \text{ ampere } (1\text{ A}) = 1 \text{ coulomb per second } (1\text{ C}^{-1}\text{ s})$$

Current, as defined by Eq. (1.8) is a scalar, because both the charge and time are scalars. If a current splits into branches, the magnitude of the partial currents must add to yield the magnitude of the current in the original conductor (i_0), because the charge is conserved. Thus, for example, for two branches, this can be expressed as:

$$i_0 = i_1 + i_2 \tag{1.9}$$

where i_1 and i_2 are currents in the two branches, respectively (see Fig. 1.10)

In an electric loop, an addition of a battery imposes an electric potential between the ends of the loop that are connected to the terminals of the battery. The battery thus produces an electric field within the loop, from terminal to terminal and the field causes charges to move around the loop. This movement of charges is a current i. The direction of flow of the current is shown from the positive to the negative terminal. The positive

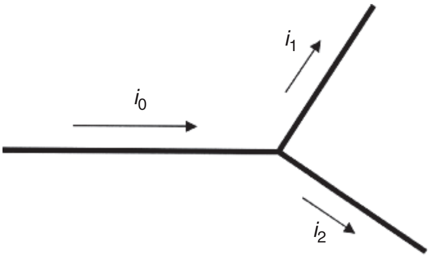

FIGURE 1.10 Current splitting at a junction into two branches.

charge carriers as they are often called will move away from the positive carrier and toward the negative terminal (see Section 1.7). Still, for historical reasons we use the following convention: *A current arrow is drawn in the direction in which positive charge carriers would move, even if the actual charge carriers are negative and move in the opposite direction* [5].

We can use this convention because in *most* situations, the assumed motion of positive charge carriers in one direction has the same effect as the actual motion of negative charge carriers in the opposite direction. When the effect is not the same, the convention is dropped and the actual motion is described.

1.9 RESISTANCE AND RESISTIVITY

If we apply the same potential difference between the ends of geometrically similar rods of copper and glass, very different currents result. The characteristic of the conductor that enters here is its resistance. We determine the resistance between any two points of a conductor by applying a potential difference V between those points and measuring the current I that results. The resistance R is then

$$R = \frac{V}{i} \tag{1.10}$$

The SI unit for resistance is the ohm (symbol Ω). That is,

$$1\,\Omega = 1 \text{ volt per ampere} = 1\,\mathrm{VA}^{-1}$$

If we focus on the *electric field* E at a point in a resistive material instead on the *potential difference* V across a particular resistor, we deal with the *current density* J at the point in question instead of the current i through the resistor. Then we are dealing with the resistivity of the *material* instead of the resistance R of the object. The resistivity ρ of the material is defined as:

$$\rho = \frac{E}{J} \tag{1.11}$$

The unit of resistivity is

$$\frac{\text{unit }(E)}{\text{unit }(J)} = \frac{\text{V m}^{-1}}{\text{A m}^{-2}} = \left(\frac{\text{V}}{\text{A}}\right)\text{m} = \Omega\,\text{m (ohm-meter)}$$

The reciprocal of the resistivity of a material is its conductivity (σ) defined as:

$$\sigma = \frac{1}{\rho} \tag{1.12}$$

The SI unit of conductivity is siemens, S, where 1 S = 1 Ω^{-1}.

Values for the resistivity of some materials are listed in Table 1.7.

TABLE 1.7 Values of Resistivities of Some Materials at Room Temperature

Material	Volume Resistivity ($\Omega \cdot$ m)
Typical Metals	
Silver	1.62×10^{-8}
Copper	1.69×10^{-8}
Aluminum	2.75×10^{-8}
Tungsten	5.25×10^{-8}
Iron	9.68×10^{-8}
Platinum	10.6×10^{-8}
Manganin[a]	48.2×10^{-8}
Typical Semiconductors	
Silicon, pure	2.5×10^{3}
Silicon, n-type[b]	8.7×10^{-4}
Silicon, p-type[c]	2.8×10^{-3}
Typical Insulators	
Glass	10^{10}–10^{14}
Fused quartz	$\sim 10^{16}$
Polyethylene	$\sim 10^{19}$
Polytetrafluoroethylene	$>10^{20}$
Polyisobutylene	$>10^{17}$

[a] An alloy specifically designed to have a small value of α.

[b] Pure silicon doped with phosphorus impurities.

[c] Pure silicon doped with aluminum impurities.

1.10 OHM'S LAW

Ohm's law is valid for circuits, expresses the relationship between current, voltage, and resistance:

$$E = IR \tag{1.13}$$

where $E =$ potential (in V); $I =$ current (in A); and $R =$ resistance (in Ω).

Ohm's law is an assertion that the current through a device is *always* directly proportional to the potential applied to the device. A conducting device obeys Ohm's law when the resistance of the device is independent of the magnitude and polarity of the applied potential difference. There are exceptions to Ohm's law, such as applications in modern microelectronics [6].

1.11 SEMICONDUCTORS

A *semiconductor* is a material that has an electrical conductivity due to flowing electrons (as opposed to ionic conductivity), which is intermediate in magnitude between that of a conductor and an insulator; this means roughly in the range 10^{1}–10^{-10} S m^{-1}) siemens per meter. Devices made from semiconductor materials are the foundation of modern electronics, including the radio, computers, telephones, and many other devices.

In a metallic conductor, current is carried by the flow of electrons. In semiconductors, current is often schematized as being carried either by the flow of electrons or by the flow of positively charged "holes" in the electron structure of the material. Actually, however, in both cases only electron movements are involved. In other words, semiconductors can be defined as materials with few conduction electrons, but with available conduction-level states that are close, in energy, to their valence bands.

Common semiconducting materials are crystalline solids, but amorphous and liquid semiconductors are also known. These include hydrogenated amorphous silicon and mixtures of arsenic, selenium, and tellurium in a variety of proportions. Such compounds share with better known semiconductors intermediate conductivity and a rapid variation of conductivity with temperature, as well as occasional negative resistance. Such disordered materials lack the rigid crystalline structure of conventional semiconductors, such as silicon, and are generally used in thin-film structures, which are less demanding when it concerns the electronic quality of the material and thus are relatively insensitive to impurities and radiation damage. Organic semiconductors, that is, organic materials with properties resembling conventional semiconductors, are also known.

Silicon is used to create most semiconductors commercially. Dozens of other materials are used, including germanium, gallium arsenide, and silicon carbide. A pure semiconductor is often called an “intrinsic” semiconductor. The electronic properties and the conductivity of a semiconductor can be changed in a controlled manner by adding very small quantities of other elements, called “dopants,” to the intrinsic material. In crystalline silicon, typically this is achieved by adding impurities of boron or phosphorus to the melt and then allowing the melt to solidify into the crystal. This process is called “doping.” The doping atoms contribute electrons to the conduction band [7].

1.12 SUPERCONDUCTIVITY AND SUPERCONDUCTORS

Superconductivity was discovered in 1911. The observation was that the resistivity of mercury absolutely disappears at temperatures below $\sim$4 K (-452.5°F). Currents created in a superconducting ring, for example, have persisted for several years without diminution; the electrons making up the current require a force and source of energy at start-up time, but not thereafter [8].

The reason superconductivity was not applied often enough was that the cost of producing the extremely low temperatures required to achieve this effect was prohibitively high. In 1986, however, new ceramic materials were discovered that became superconductive at considerably higher (hence, cheaper to produce) temperatures.

Superconductivity is much different from conductivity. In fact, the best of the normal conductors (e.g., silver and copper) cannot become superconducting at any temperature, and the new ceramic superconductors are actually insulators when they are not at low enough temperatures to be in the superconducting state [8].

One explanation of superconductivity is that the electrons that make up the current move in coordinated pairs. One of the electrons in a pair electrically distort the molecular structure of the superconducting material as it moves through, creating a nearby short-lived concentration of positive charge. The other electron in the pair may then be attracted toward this positive charge. According to theory, such coordination between electrons would prevent them from colliding with the molecules and thus would eliminate electrical resistance [9].

1.13 PIEZOELECTRICITY

Piezoelectricity is the charge that accumulates in certain solid materials (notably crystals, certain ceramics, and biological matter (e.g., bone, deoxyribonucleic acid (DNA) and various proteins) in response to applied mechanical strain [10, 11]. The word piezoelectricity means electricity resulting from pressure. It is derived from the Greek *piezo* or *piezein*, which means to squeeze or press, and *electric* or *electron*, which stands for amber, an ancient source of electric charge. Piezoelectricity is the direct result of the *piezoelectric effect*.

The piezoelectric effect is understood as the linear electromechanical interaction between the mechanical and the electrical state in crystalline materials with no inversion symmetry [11, 12]. The piezoelectric effect is a reversible process in that materials exhibiting the direct piezoelectric effect (the internal generation of electrical charge resulting from an applied mechanical force) also exhibit the reverse piezoelectric effect (the internal generation of a mechanical force resulting from an applied electrical field).

Piezoelectricity is found in useful applications, such as the production and detection of sound, generation of high voltages, electronic frequency generation, microbalances, and ultrafine focusing of optical assemblies. It is also the basis for a number of scientific instrumental techniques with atomic resolution, the scanning probe microscopy techniques, sensors, transducers, microphones, loudspeakers, inkjet printers, fuel injectors, piezoelectric motors, and everyday uses (e.g., acting as the ignition source for cigarette lighters and push–start propane barbecue grills).

1.14 PYROELECTRICITY

Pyroelectricity (from the Greek *pyr*, fire, and electricity) is the ability of certain materials to generate a temporary voltage when they are heated or cooled [12]. The change in temperature slightly modifies the positions of the atoms within the crystal structure, such that the polarization of the material changes. This polarization change gives rise to a voltage across the crystal. If the temperature stays constant at its new value, the pyroelectric voltage gradually disappears due to leakage current (the leakage can be due to electrons moving through the crystal, ions moving through the air, current leaking through a voltmeter attached across the crystal, etc.) [13, 14]. Pyroelectricity should not be confused with thermoelectricity: In a typical demonstration of pyroelectricity, the whole crystal is changed from one temperature to another, and the result is a temporary voltage across the crystal. In a typical demonstration of thermoelectricity, one side of the material is kept at one temperature. The other side at a different temperature. The result is a *permanent* voltage across the crystal. All pyroelectric materials are also piezoelectric, the two properties being closely related. However, some piezoelectric materials have a crystal symmetry that does not allow pyroelectricity.

1.15 FERROELECTRICITY

Ferroelectricity is a spontaneous electric polarization of a material. Ferroelectric materials may exhibit a spontaneous dipole moment, the direction of which can be switched between equivalent states by the application of an external electric field. The term ferroelectricity is related to the concept of ferromagnetism, which has to do with the creation of a magnetic moment [15, 16]. Ferroelectrics are a subgroup of pyroelectrics [15].

Placing a ferroelectric material between two conductive plates creates a ferroelectric capacitor. Ferroelectric capacitors exhibit nonlinear properties and usually have very high dielectric constants. The fact that the internal electric dipoles can be forced to change their direction by the application of an external voltage gives rise to *hysteresis* in the "polarization versus voltage" property of the capacitor. In this case, polarization is defined as the total charge stored on the plates of the capacitor divided by the area of the plates. Hysteresis means memory and ferroelectric capacitors are used to make ferroelectric random access memory (RAM) for computers [17] and radio frequency identification (RFID) cards [18].

1.16 METHODS FOR GENERATING ELECTRIC ENERGY

1.16.1 Batteries

The simplest sources of electrical energy are *batteries*. These are devices in which energy is generated by chemical reactions once the active components are allowed to circulate their electrons in an external circuit. The energy that is stored chemically is potential energy available to do electrical work. In rechargeable batteries, the chemistry is available and energy can be put back into the battery. The most common batteries are

- *Zinc–carbon batteries* are the most common "flashlight" batteries, available in regular and heavy-duty types. Their electrodes are zinc and carbon with an acidic paste between them that serves as the electrolyte. They are not recommended for electronic application.

- *Alkaline batteries* last 300–800% longer than zinc batteries, depending on their application. The electrodes of alkaline batteries are zinc and manganese oxide, with an alkaline electrolyte.
- *Nickel–cadmium batteries* are very popular in the majority of commercially available rechargeable products. The electrodes are nickel hydroxide and cadmium, with potassium hydroxide as the electrolyte. Their shortcoming is their tendency to develop "memory." Therefore it is recommended to discharge them fully before recharging.
- *Lithium iodide batteries* are designed to supply a small amount of power for a long period of time. They are widely used in power back-up systems in computers and wrist watches, pacemakers and hearing aids.
- *Lithium ion batteries* have a favorable power/weight ratio and are used widely in high-end laptop computers and cell telephones. They are rechargeable. More details on this subject are in Section 6.5.
- *Nickel–metal hydride batteries* are rapidly replacing the nickel–cadmium types because they do not suffer from memory effect.
- *Silver–zinc batteries* are used in aeronautical applications and in some miniature consumer electronic devices.
- *Zinc–air batteries* are light weight and rechargeable.
- *Zinc–mercury oxide* batteries are light, supply a small amount of power over a long period of time, and are used in hearing aids.
- *Lead–acid batteries* contain one plate made of lead and another plate made of lead dioxide, with a strong sulfuric acid electrolyte in which the plates are immersed. They are used mainly in automobiles.
- *Gelled electrolyte batteries* fall into the same category as lead–acid types and are most widely used in the uninterruptible power supplies (UPS) for computer systems, burglar alarms, and emergency lights.

1.16.2 Fuel Cells

Other sources of electrical energy are *fuel cells*. Fuel cells are different from conventional electrochemical cell batteries in that they consume reactant from an external source, which must be replenished: a thermodynamically open system. By contrast, batteries store electrical energy chemically, and hence represent a thermodynamically closed system. A fuel cell is an electrochemical cell that converts a source fuel into an electric current. It generates electricity inside a cell through reactions between a fuel and an oxidant, triggered in the presence of an electrolyte. The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. Fuel cells can operate continuously as long as the necessary reactant and oxidant flows are maintained. Currently, the most commonly used fuel is hydrogen. More on this subject is found in Section 6.4.2.

1.16.3 Solar Cells

Solar cells (photovoltaic devices) generate power by absorbing sunlight. Currently, commercial solar cells are made from inorganic substances, such as single-crystal silicon, gallium, and others. Organic solar cells, including polymeric types are being developed. For more details, see Section 6.1.2.

1.16.4 Commercial Facilities

Electricity for industrial and residential use is most often generated at a power station by electromechanical generators, primarily driven by heat engines fueled by chemical combustion or nuclear fission, but also by other means, such as the kinetic energy of flowing water and wind. There are many other technologies that can be and are used to generate electricity, such as solar photovoltaics (see Section 1.16.3), and geothermal power.

Depending on the way the electric energy is generated, it can be in the form of direct current (dc) and alternating current (ac), the latter being defined by its frequency. For commercial electric utilities the most common frequencies are 60 and 50 Hz depending on the country. Currently in North America the frequency is 60 Hz and in most European countries 50 Hz. Furthermore, it is possible to generate alternating electric fields by specialized devices with frequencies much lower and higher than the above.

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