

HISTORICAL PERSPECTIVE

Materials are probably more deep-seated in our culture than most of us realize. Transportation, housing, clothing, communication, recreation, and food production – virtually every segment of our everyday lives is influenced to one degree or another by materials. Historically, the development and advancement of societies have been intimately tied to the members' ability to produce and manipulate materials to fill their needs. In fact, early civilizations have been designated by the level of their materials development (Stone Age, Bronze Age, Iron Age).¹ The earliest humans had access to only a very limited number of materials, those that occur naturally: stone, wood, clay, skins, and so on. With time they discovered techniques for producing materials that had properties superior to those of the natural ones; these new materials included pottery and various metals. Furthermore, it was discovered that the properties of a material could be altered by heat treatments and by the addition of other substances. At this point, materials utilization was totally a selection process that involved deciding from a given, rather limited set of materials the one best suited for an application by virtue of its characteristics.

It was not until relatively recent times that scientists came to understand the relationships between the structural elements of materials and their properties. This knowledge, acquired over approximately the past 100 years, has empowered them to fashion, to a large degree, the characteristics of materials. Thus, tens of thousands of different materials have evolved with rather specialized characteristics that meet the needs of our modern and complex society; these include metals, plastics, glasses, and fibers.

The development of many technologies that make our existence so comfortable has been intimately associated with the accessibility of suitable materials. An advancement in the understanding of a material type is often the forerunner to the stepwise progression of a technology. For example, automobiles would not have been possible without the availability of inexpensive steel or some other comparable substitute. In our contemporary era, sophisticated electronic devices rely on components that are made from what are called semiconducting materials.

Atomic structure and interatomic bonding

Electrons in Atoms

The Periodic Table

This chapter began with a survey of the fundamentals of atomic structure, presenting the Bohr and wave-mechanical models of electrons in atoms. Whereas the Bohr model assumes electrons to be particles orbiting the nucleus in discrete paths, in wave mechanics we consider them to be wave-like and treat electron position in terms of a probability distribution. Electron energy states are specified in terms of quantum numbers that give rise to electron shells and subshells. The electron configuration of an atom corresponds to the manner in which these shells and subshells are filled with electrons in compliance with the Pauli exclusion principle. The periodic table of the elements is generated by arrangement of the various elements according to valence electron configuration.

Bonding Forces and Energies

Primary Interatomic Bonds

Atomic bonding in solids may be considered in terms of attractive and repulsive forces and energies. The three types of primary bond in solids are ionic, covalent, and metallic. For ionic bonds, electrically charged ions are formed by the transference of valence electrons from one atom type to another; forces are coulombic. There is a sharing of valence electrons between adjacent atoms when bonding is covalent. With metallic bonding, the valence electrons form a "sea of electrons" that is uniformly dispersed around the metal ion cores and acts as a form of glue for them.

Secondary Bonding or van der Waals Bonding

Both van der Waals and hydrogen bonds are termed secondary, being weak in comparison to the primary ones. They result from attractive forces between electric dipoles, of which there are two types – induced and permanent. For the hydrogen bond, highly polar molecules form when hydrogen covalently bonds to a nonmetallic element such as fluorine.

Key

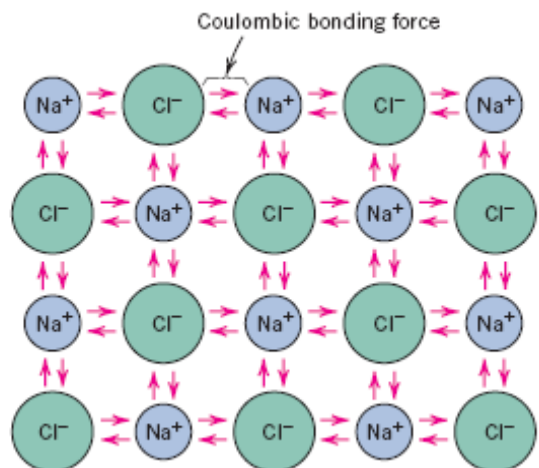
- Atomic number
- Symbol
- Atomic weight

Color Coding:

- Light Blue: Metal
- Dark Blue: Nonmetal
- Blue-White: Intermediate

1 H 1.0080	2 He 4.0026																	
3 Li 6.941	4 Be 9.0122											5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180	
11 Na 22.990	12 Mg 24.305							13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948					
19 K 39.098	20 Ca 40.08	21 Sc 44.956	22 Ti 47.87	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.69	29 Cu 63.54	30 Zn 65.41	31 Ga 69.72	32 Ge 72.64	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80	
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.4	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.30	
55 Cs 132.91	56 Ba 137.34	Rare earth series	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.2	76 Os 190.23	77 Ir 192.2	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.19	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)	
87 Fr (223)	88 Ra (226)	Acti- nide series	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (264)	108 Hs (277)	109 Mt (268)	110 Ds (281)									
Rare earth series		57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.35	63 Eu 151.96	64 Gd 157.25	65 Tb 158.92	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97		
Actinide series		89 Ac (227)	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)		

The periodic table of the elements. The numbers in parentheses are the atomic weights of the most stable or common isotopes.



Schematic representation of ionic bonding in sodium chloride (NaCl).

The Structure of Crystalline Solids

Fundamental Concepts

Unit Cells

Atoms in crystalline solids are positioned in orderly and repeated patterns that are in contrast to the random and disordered atomic distribution found in noncrystalline or amorphous materials. Atoms may be represented as solid spheres, and, for crystalline solids, crystal structure is just the spatial arrangement of these spheres.

The various crystal structures are specified in terms of parallelepiped unit cells, which are characterized by geometry and atom positions within.

Metallic Crystal Structures

Most common metals exist in at least one of three relatively simple crystal structures:

face-centered cubic (FCC), body-centered cubic (BCC), and hexagonal closepacked(HCP). Two features of a crystal structure are coordination number (or number of nearest-neighbor atoms) and atomic packing factor (the fraction of solid sphere volume in the unit cell). Coordination number and atomic packing factor are the same for both FCC and HCP crystal structures, each of which may be generated by the stacking of close-packed planes of atoms.

Point Coordinates

Crystallographic Directions

Crystallographic Planes

Crystallographic points, directions, and planes are specified in terms of indexing schemes. The basis for the determination of each index is a coordinate axis system defined by the unit cell for the particular crystal structure. The location of a point within a unit cell is specified using coordinates that are fractional multiples of the cell edge lengths. Directional indices are computed in terms of the vector projection on each of the coordinate axes, whereas planar indices are determined from the reciprocals of axial intercepts. For hexagonal unit cells, a four-index scheme for both directions and planes is found to be more convenient.

Linear and Planar Densities

Crystallographic directional and planar equivalencies are related to atomic linear and planar densities, respectively. The atomic packing (i.e., planar density) of spheres in a crystallographic plane depends on the indices of the plane as well as the crystal structure. For a given crystal structure, planes having identical atomic packing yet different Miller indices belong to the same family.

Single Crystals

Polycrystalline Materials

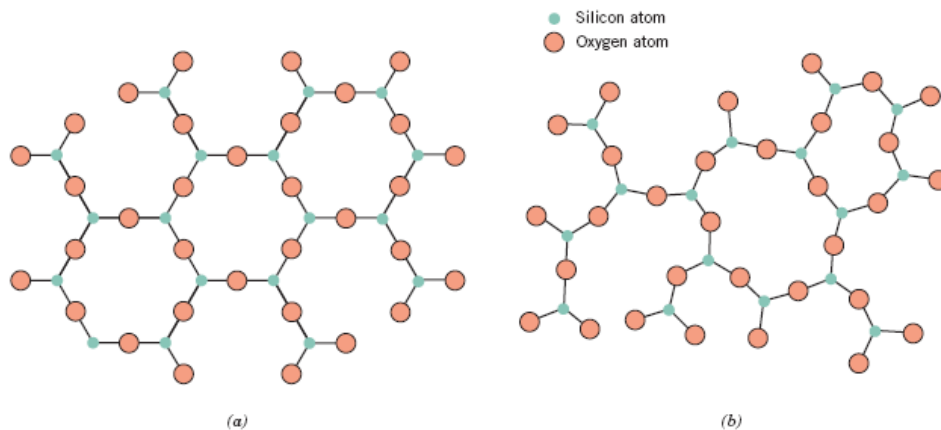
Single crystals are materials in which the atomic order extends uninterrupted over the entirety of the specimen; under some circumstances, they may have flat faces and regular geometric shapes. The vast majority of crystalline solids, however, are polycrystalline, being composed of many small crystals or grains having different crystallographic orientations.

Crystal SystemsPolymorphism and AllotropyAnisotropy

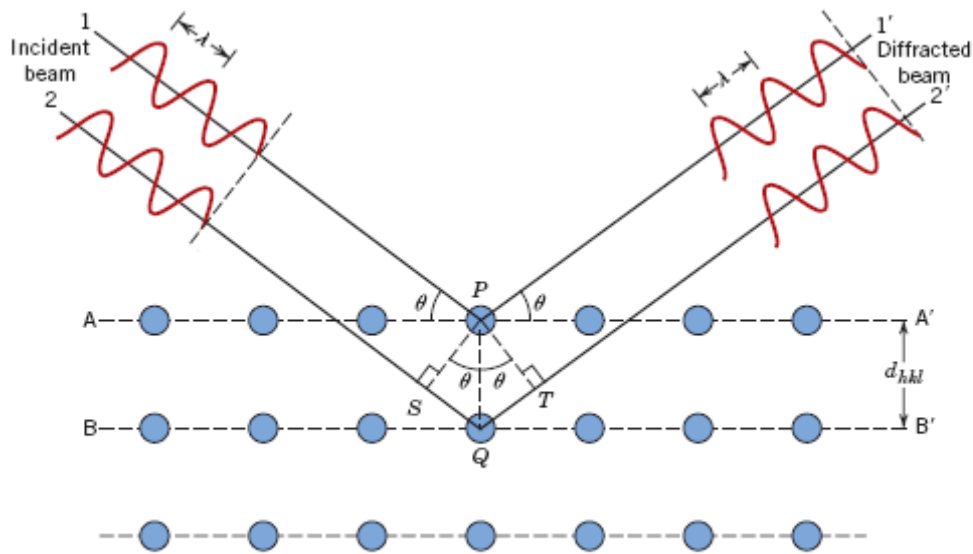
Other concepts introduced in this chapter were: crystal system (a classification scheme for crystal structures on the basis of unit cell geometry), polymorphism (or allotropy) (when a specific material can have more than one crystal structure), and anisotropy (the directionality dependence of properties).

X-Ray Diffraction: Determination of Crystal Structures

X-ray diffractometry is used for crystal structure and interplanar spacing determinations. A beam of x-rays directed on a crystalline material may experience diffraction (constructive interference) as a result of its interaction with a series of parallel atomic planes according to Bragg's law. Interplanar spacing is a function of the Miller indices and lattice parameter(s) as well as the crystal structure.



Two-dimensional schemes of the structure of (a) crystalline silicon dioxide and (b) noncrystalline silicon dioxide



Diffraction of x-rays by planes of atoms (A-A' and B-B').

Imperfections in Solids

Vacancies and Self-Interstitials

All solid materials contain large numbers of imperfections or deviations from crystalline perfection. The several types of imperfection are categorized on the basis of their geometry and size. Point defects are those associated with one or two atomic positions, including vacancies (or vacant lattice sites), self-interstitials (host atoms that occupy interstitial sites), and impurity atoms.

Impurities in Solids

A solid solution may form when impurity atoms are added to a solid, in which case the original crystal structure is retained and no new phases are formed. For substitutional solid solutions, impurity atoms substitute for host atoms, and appreciable solubility is possible only when atomic diameters and electronegativities for both atom types are similar, when both elements have the same crystal structure, and when the impurity atoms have a valence that is the same as or less than the host material. Interstitial solid solutions form for relatively small impurity atoms that occupy interstitial sites among the host atoms.

Specification of Composition

Composition of an alloy may be specified in weight percent or atom percent. The basis for weight percent computations is the weight (or mass) of each alloy constituent relative to the total alloy weight. Atom percents are calculated in terms of the number of moles for each constituent relative to the total moles of all the elements in the alloy.

Dislocations – Linear Defects

Dislocations are one-dimensional crystalline defects of which there are two pure types: edge and screw. An edge may be thought of in terms of the lattice distortion along the end of an extra half-plane of atoms; a screw, as a helical planar ramp. For mixed dislocations, components of both pure edge and screw are found. The magnitude and direction of lattice distortion associated with a dislocation are specified by its Burgers vector. The relative orientations of Burgers vector and dislocation line are (1) perpendicular for edge, (2) parallel for screw, and (3) neither perpendicular nor parallel for mixed.

Interfacial Defects

Bulk or Volume Defects

Atomic Vibrations

Other imperfections include interfacial defects [external surfaces, grain boundaries(both small- and high-angle), twin boundaries, etc.], volume defects (cracks, pores, etc.), and atomic vibrations. Each type of imperfection has some influence on the properties of a material.

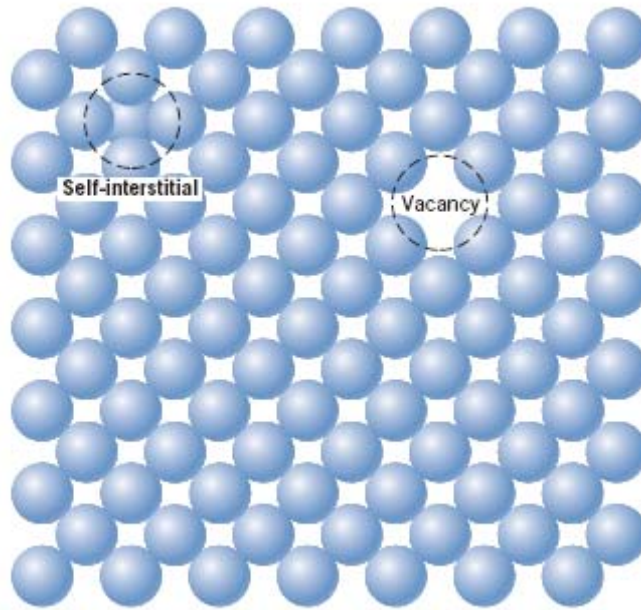
Microscopic Techniques

Many of the important defects and structural elements of materials are of microscopic dimensions, and observation is possible only with the aid of a microscope. Both optical and electron microscopes are employed, usually in conjunction with photographic equipment. Transmissive and reflective modes are possible for each microscope type; preference is dictated by the nature of the specimen as well as the structural element or defect to be examined.

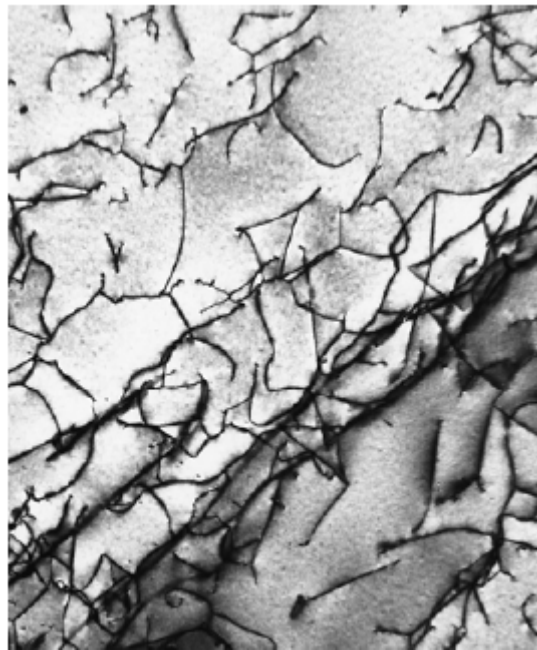
More recent scanning probe microscopic techniques have been developed that generate topographical maps representing the surface features and characteristics of the specimen. Examinations on the atomic and molecular levels are possible using these techniques.

Grain Size Determination

Grain size of polycrystalline materials is frequently determined using photomicrographic techniques. Two methods are commonly employed: intercept and standard comparison charts.



*Two-dimensional representations of a vacancy and a self-interstitial. (Adapted from W. G. Moffatt, G.W. Pearsall, and J.Wulff, *The Structure and Properties of Materials, Vol. I, Structure*, p. 77. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)*



A transmission electron micrograph of a titanium alloy in which the dark lines are dislocations. (Courtesy of M. R. Plichta, Michigan Technological University.)

Mechanical Properties

Concepts of Stress and Strain

Stress–Strain Behavior

Elastic Properties of Materials

True Stress and Strain

A number of the important mechanical properties of materials, predominantly metals, have been discussed in this chapter. Concepts of stress and strain were first introduced. Stress is a measure of an applied mechanical load or force, normalized to take into account cross-sectional area. Two different stress parameters were defined—engineering stress and true stress. Strain represents the amount of deformation induced by a stress; both engineering and true strains are used. Some of the mechanical characteristics of metals can be ascertained by simple stress–strain tests. There are four test types: tension, compression, torsion, and shear. Tensile are the most common. A material that is stressed first undergoes elastic, or nonpermanent, deformation, wherein stress and strain are proportional. The constant of proportionality is the modulus of elasticity for tension and compression, and is the shear modulus when the stress is shear. Poisson’s ratio represents the negative ratio of transverse and longitudinal strains.

Tensile Properties

The phenomenon of yielding occurs at the onset of plastic or permanent deformation; yield strength is determined by a strain offset method from the stress–strain behavior, which is indicative of the stress at which plastic deformation begins. Tensile strength corresponds to the maximum tensile stress that may be sustained by a specimen, whereas percents elongation and reduction in area are measures of ductility—the amount of plastic deformation that has occurred at fracture. Resilience is the capacity of a material to absorb energy during elastic deformation; modulus of resilience is the area beneath the engineering stress–strain curve up to the yield point. Also, static toughness represents the energy absorbed during the fracture of a material, and is taken as the area under the entire engineering stress–strain curve. Ductile materials are normally tougher than brittle ones.

Hardness

Hardness is a measure of the resistance to localized plastic deformation. In several popular hardness-testing techniques (Rockwell, Brinell, Knoop, and Vickers) a small indenter is forced into the surface of the material, and an index number is determined on the basis of the size or depth of the resulting indentation. For many metals, hardness and tensile strength are approximately proportional to each other.

Variability of Material Properties

Measured mechanical properties (as well as other material properties) are not exact and precise quantities, in that there will always be some scatter for the measured data. Typical material property values are commonly specified in terms of averages, whereas magnitudes of scatter may be expressed as standard deviations.

Design/Safety Factors

As a result of uncertainties in both measured mechanical properties and inservice applied stresses, design or safe stresses are normally utilized for design purposes. For ductile materials, safe stress is the ratio of the yield strength and the factor of safety.

Corrosion and Degradation of Materials

Electrochemical Considerations

Metallic corrosion is ordinarily electrochemical, involving both oxidation and reduction reactions. Oxidation is the loss of the metal atom's valence electrons; the resulting metal ions may either go into the corroding solution or form an insoluble compound. During reduction, these electrons are transferred to at least one other chemical species. The character of the corrosion environment dictates which of several possible reduction reactions will occur. Not all metals oxidize with the same degree of ease, which is demonstrated with a galvanic couple; when in an electrolyte, one metal (the anode) will corrode, whereas a reduction reaction will occur at the other metal (the cathode). The magnitude of the electric potential that is established between anode and cathode is indicative of the driving force for the corrosion reaction. The standard emf and galvanic series are simply rankings of metallic materials on the basis of their tendency to corrode when coupled to other metals. For the standard emf series, ranking is based on the magnitude of the voltage generated when the standard cell of a metal is coupled to the standard hydrogen electrode at The galvanic series consists of the relative reactivities of metals and alloys in seawater. The half-cell potentials in the standard emf series are thermodynamic parameters that are valid only at equilibrium; corroding systems are not in equilibrium. Furthermore, the magnitudes of these potentials provide no indication as to the rates at which corrosion reactions occur.

Corrosion Rates

The rate of corrosion may be expressed as corrosion penetration rate, that is, the thickness loss of material per unit of time. Mils per year and millimeters per year are the common units for this parameter. Alternatively, rate is proportional to the current density associated with the electrochemical reaction.

Prediction of Corrosion Rates

Corroding systems will experience polarization, which is the displacement of each electrode potential from its equilibrium value; the magnitude of the displacement is termed the overvoltage. The corrosion rate of a reaction is limited by polarization, of which there are two types—activation and concentration. Polarization data are plotted as potential versus the logarithm of current density. The corrosion rate for a particular reaction may be computed using the current density associated with the intersection point of oxidation and reduction polarization curves.

Passivity

A number of metals and alloys passivate, or lose their chemical reactivity, under some environmental circumstances. This phenomenon is thought to involve the formation of a thin protective oxide film. Stainless steels and aluminum alloys exhibit this type of behavior. The active-to-passive behavior may be explained by the alloy's S-shaped electrochemical potential-versus-log current density curve. Intersections with reduction polarization curves in active and passive regions correspond, respectively, to high and low corrosion rates.

Forms of Corrosion

Metallic corrosion is sometimes classified into eight different forms: uniform attack, galvanic corrosion, crevice corrosion, pitting, intergranular corrosion, selective leaching, erosion-corrosion, and stress corrosion. Hydrogen embrittlement, a type of failure sometimes observed in corrosion environments, was also discussed.

Corrosion Prevention

The measures that may be taken to prevent, or at least reduce, corrosion include material selection, environmental alteration, the use of inhibitors, design changes, application of coatings, and cathodic protection.

Oxidation

Oxidation of metallic materials by electrochemical action is also possible in dry, gaseous atmospheres. An oxide film forms on the surface which may act as a barrier to further oxidation if the volumes of metal and oxide film are similar, that is, if the Pilling–Bedworth ratio is near unity. The kinetics of film formation may follow parabolic, linear, or logarithmic rate laws.

Corrosion of Ceramic Materials

Ceramic materials, being inherently corrosion resistant, are frequently utilized at elevated temperatures and/or in extremely corrosive environments.

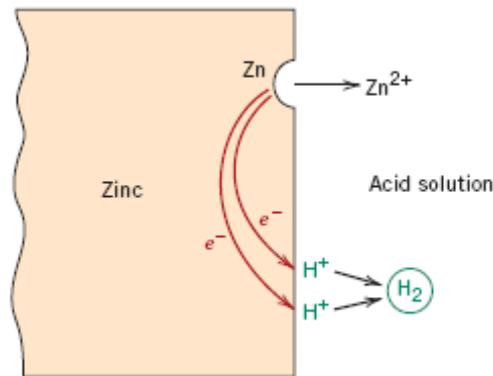
Swelling and Dissolution

Bond Rupture

Weathering

Polymeric materials deteriorate by noncorrosive processes. Upon exposure to liquids, they may experience degradation by swelling or dissolution. With swelling, solute molecules actually fit into the molecular structure. Scission, or the severance of molecular chain bonds, may be induced by radiation, chemical reactions, or heat.

This results in a reduction of molecular weight and a deterioration of the physical and chemical properties of the polymer.



The electrochemical reactions associated with the corrosion of zinc in an acid solution. (From M. G. Fontana, Corrosion Engineering, 3rd edition. Copyright © 1986 by McGraw-Hill Book Company. Reproduced with permission.)

Electrical Properties

Ohm's Law

Electrical Conductivity

The ease with which a material is capable of transmitting an electric current is expressed in terms of electrical conductivity or its reciprocal, resistivity. On the basis of its conductivity, a solid material may be classified as a metal, a semiconductor, or an insulator.

Electronic and Ionic Conduction

Energy Band Structures in Solids

Conduction in Terms of Band and Atomic Bonding Models

For most materials, an electric current results from the motion of free electrons, which are accelerated in response to an applied electric field. The number of these free electrons depends on the electron energy band structure of the material. An electron band is just a series of electron states that are closely spaced with respect to energy, and one such band may exist for each electron subshell found in the isolated atom. By "electron energy band structure" is meant the manner in which the outermost bands are arranged relative to one another and then filled with electrons. A distinctive band structure type exists for metals, for semiconductors, and for insulators.

An electron becomes free by being excited from a filled state in one band, to an available empty state above the Fermi energy. Relatively small energies are required for electron excitations in metals, giving rise to large numbers of free electrons. Larger energies are required for electron excitations in

semiconductors and insulators, which accounts for their lower free electron concentrations and smaller conductivity values.

Electron Mobility

Free electrons being acted on by an electric field are scattered by imperfections in the crystal lattice. The magnitude of electron mobility is indicative of the frequency of these scattering events. In many materials, the electrical conductivity is proportional to the product of the electron concentration and the mobility.

Electrical Resistivity of Metals

For metallic materials, electrical resistivity increases with temperature, impurity content, and plastic deformation. The contribution of each to the total resistivity is additive.

Intrinsic Semiconduction

Extrinsic Semiconduction

The Temperature Dependence of Carrier Concentration

Factors That Affect Carrier Mobility

Semiconductors may be either elements (Si and Ge) or covalently bonded compounds. With these materials, in addition to free electrons, holes (missing electrons in the valence band) may also participate in the conduction process. On the basis of electrical behavior, semiconductors are classified as either intrinsic or extrinsic. For intrinsic behavior, the electrical properties are inherent in the pure material, and electron and hole concentrations are equal; electrical behavior is dictated by impurities for extrinsic semiconductors. Extrinsic semiconductors may be either *n*- or *p*-type depending on whether electrons or holes, respectively, are the predominant charge carriers. Donor impurities introduce excess electrons; acceptor impurities introduce excess holes. The electrical conductivity of semiconducting materials is particularly sensitive to impurity type and content, as well as to temperature. The addition of even minute concentrations of some impurities enhances the conductivity drastically. Furthermore, with rising temperature the intrinsic carrier concentration increases dramatically. For extrinsic semiconductors, with increasing impurity dopant content, the room-temperature carrier concentration increases whereas carrier mobility diminishes.

Semiconductor Devices

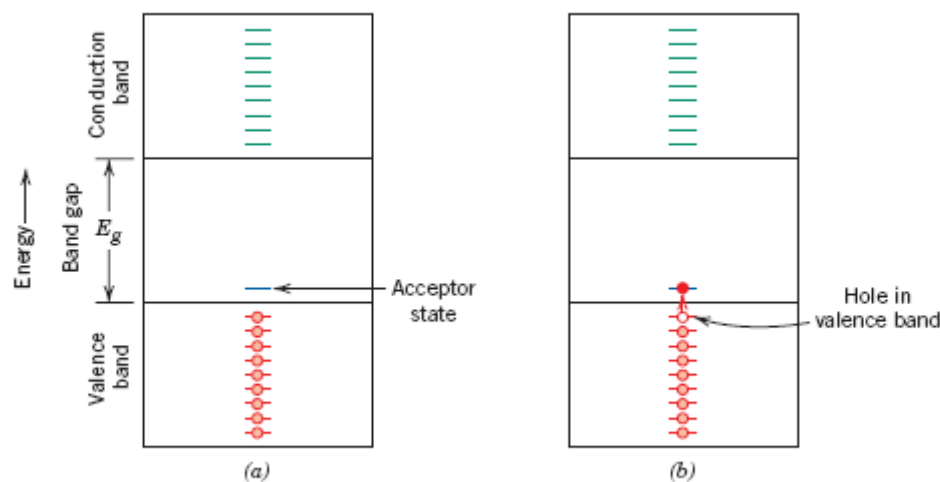
A number of semiconducting devices employ the unique electrical characteristics of these materials to perform specific electronic functions. Included are the *p-n* rectifying junction, and junction and MOSFET transistors. Transistors are used for amplification of electrical signals, as well as for switching devices in computer circuitries.

CapacitanceField Vectors and PolarizationTypes of PolarizationFrequency Dependence of the Dielectric Constant

Dielectric materials are electrically insulative, yet susceptible to polarization in the presence of an electric field. This polarization phenomenon accounts for the ability of the dielectrics to increase the charge storing capability of capacitors, the efficiency of which is expressed in terms of a dielectric constant. Polarization results from the inducement by or orientation with the electric field of atomic or molecular dipoles; a dipole is said to exist when there is a net spatial separation of positively and negatively charged entities. Possible polarization types include electronic, ionic, and orientation; not all types need be present in a particular dielectric. For alternating electric fields, whether a specific polarization type contributes to the total polarization and dielectric constant depends on frequency; each polarization mechanism ceases to function when the applied field frequency exceeds its relaxation frequency.

FerroelectricityPiezoelectricity

Also included in this chapter were brief discussions of two other electrical phenomena. Ferroelectric materials are those that may exhibit polarization spontaneously, that is, in the absence of any external electric field. Finally, piezoelectricity is the phenomenon whereby polarization is induced in a material by the imposition of external forces..



(a) Energy band scheme for an acceptor impurity level located within the band gap and just above the top of the valence band. (b) Excitation of an electron into the acceptor level, leaving behind a hole in the valence band.

Thermal Properties

Heat Capacity

This chapter discussed heat absorption, thermal expansion, and thermal conduction— three important thermal phenomena. Heat capacity represents the quantity of heat required to produce a unit rise in temperature for one mole of a substance; on a per-unit mass basis, it is termed specific heat. Most of the energy assimilated by many solid materials is associated with increasing the vibrational energy of the atoms; contributions to the total heat capacity by other energy-absorptive mechanisms(i.e., increased free-electron kinetic energies) are normally insignificant. For many crystalline solids and at temperatures within the vicinity of 0 K, the heat capacity measured at constant volume varies as the cube of the absolute temperature; in excess of the Debye temperature, becomes temperature independent assuming a value of approximately $3R$.

Thermal Expansion

Solid materials expand when heated and contract when cooled. The fractional change in length is proportional to the temperature change, the constant of proportionality being the coefficient of thermal expansion. Thermal expansion is reflected by an increase in the average interatomic separation, which is a consequence of the asymmetric nature of the potential energy versus interatomic spacing curve trough. The larger the interatomic bonding energy, the lower is the coefficient of thermal expansion.

Thermal Conductivity

The transport of thermal energy from high- to low-temperature regions of a material is termed thermal conduction. For steady-state heat transport, the flux is proportional to the temperature gradient along the direction of flow; the proportionality constant is the thermal conductivity. For solid materials, heat is transported by free electrons and by vibrational lattice waves, or phonons. The high thermal conductivities for relatively pure metals are due to the large numbers of free electrons, and also the efficiency with which these electrons transport thermal energy. By way of contrast, ceramics and polymers are poor thermal conductors because free-electron concentrations are low and phonon conduction predominates.

Thermal Stresses

Thermal stresses, which are introduced in a body as a consequence of temperature changes, may lead to fracture or undesirable plastic deformation. The two prime sources of thermal stresses are restrained thermal expansion (or contraction) and temperature gradients established during heating or cooling. Thermal shock is the fracture of a body resulting from thermal stresses induced by rapid temperature changes. Because ceramic materials are brittle, they are especially susceptible to this type of failure. The thermal shock resistance of many

materials is proportional to the fracture strength and thermal conductivity, and inversely proportional to both the modulus of elasticity and the coefficient of thermal expansion.

Magnetic Properties

Basic Concepts

The macroscopic magnetic properties of a material are a consequence of interactions between an external magnetic field and the magnetic dipole moments of the constituent atoms. Associated with each individual electron are both orbital and spin magnetic moments. The net magnetic moment for an atom is just the sum of the contributions of each of its electrons, wherein there will be spin and orbital moment cancellation of electron pairs.

Diamagnetism and Paramagnetism

Diamagnetism results from changes in electron orbital motion that are induced by an external field. The effect is extremely small and in opposition to the applied field. All materials are diamagnetic. Paramagnetic materials are those having permanent atomic dipoles, which are acted on individually and are aligned in the direction of an external field. Since the magnetizations are relatively small and persist only while an applied field is present, diamagnetic and paramagnetic materials are considered to be nonmagnetic.

Ferromagnetism

Large and permanent magnetizations may be established within the ferromagnetic metals (Fe, Co, Ni). Atomic magnetic dipole moments are of spin origin, which are coupled and mutually aligned with moments of adjacent atoms.

Antiferromagnetism and Ferrimagnetism

Antiparallel coupling of adjacent cation spin moments is found for some ionic materials. Those in which there is total cancellation of spin moments are termed antiferromagnetic. With ferrimagnetism, permanent magnetization is possible because spin moment cancellation is incomplete. For cubic ferrites, the net magnetization results from the divalent ions (e.g., Fe²⁺) that reside on octahedral lattice sites, the spin moments of which are all mutually aligned.

The Influence of Temperature on Magnetic Behavior

With rising temperature, increased thermal vibrations tend to counteract the dipole coupling forces in ferromagnetic and ferrimagnetic materials. Consequently, the saturation magnetization gradually diminishes with temperature, up to the Curie temperature, at which point it drops to near zero; above these materials are paramagnetic.

Domains and Hysteresis

Below its Curie temperature, a ferromagnetic or ferrimagnetic material is composed of domains—small-volume regions wherein all net dipole moments are mutually aligned and the magnetization is saturated. The total magnetization of the solid is just the appropriately weighted vector sum of the magnetizations of all these domains. As an external magnetic field is

applied, domains having magnetization vectors oriented in the direction of the field grow at the expense of domains that have unfavorable magnetization orientations. At total saturation, the entire solid is a single domain and the magnetization is aligned with the field direction. The change in domain structure with increase or reversal of a magnetic field is accomplished by the motion of domain walls. Both hysteresis (the lag of the B field behind the applied H field) as well as permanent magnetization (or remanence) result from the resistance to movement of these domain walls.

Magnetic Anisotropy

The M (or B) versus H behavior for a ferromagnetic single crystal is anisotropic – that is, dependent on the crystallographic direction along which the magnetic field is applied. The crystallographic direction for which is achieved at the lowest H field is an easy magnetization direction; for Fe, Ni, and Co easy directions are, respectively, [100], [111], and [0001].

Soft Magnetic Materials

Hard Magnetic Materials

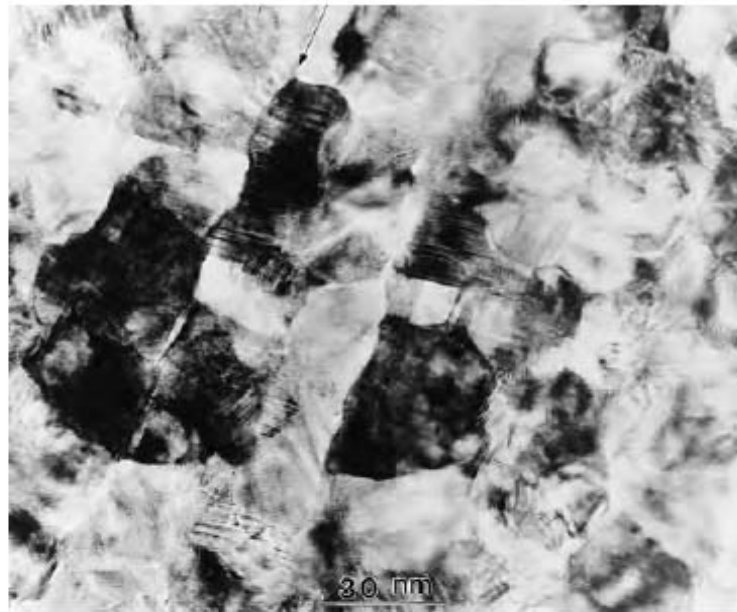
For soft magnetic materials, domain wall movement is easy during magnetization and demagnetization. Consequently, they have small hysteresis loops and low energy losses. Domain wall motion is much more difficult for the hard magnetic materials, which results in larger hysteresis loops; because greater fields are required to demagnetize these materials, the magnetization is more permanent.

Magnetic Storage

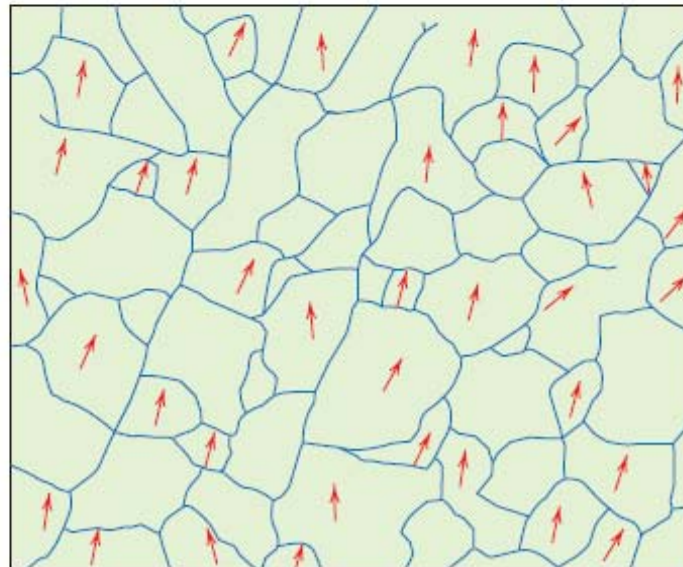
Information storage is accomplished using magnetic materials in both needle-shaped particulate and thin-film forms.

Superconductivity

Superconductivity has been observed in a number of materials, in which, upon cooling and in the vicinity of absolute zero temperature, the electrical resistivity vanishes. The superconducting state ceases to exist if temperature, magnetic field, or current density exceeds the critical value. For type I superconductors, magnetic field exclusion is complete below a critical field, and field penetration is complete once it is exceeded. This penetration is gradual with increasing magnetic field for type II materials. New complex oxide ceramics are being developed with relatively high critical temperatures, which allow inexpensive liquid nitrogen to be used as a coolant.



(a)



(b)

(a) A high-resolution transmission electron micrograph showing the microstructure of a cobalt-chromium-platinum thin film that is used as a high-density magnetic storage medium. The arrow at the top indicates the motion direction of the medium. 500,000 \times . (b) A representation of the grain structure for the electron micrograph in (a); the arrows in some of the grains indicate the texture, or the direction of easy magnetization.

Optical Properties

Electromagnetic Radiation

Light Interactions with Solids

The optical behavior of a solid material is a function of its interactions with electromagnetic radiation having wavelengths within the visible region of the spectrum. Possible interactive phenomena include refraction, reflection, absorption, and transmission of incident light.

Optical Properties of Metals

Metals appear opaque as a result of the absorption and then reemission of light radiation within a thin outer surface layer. Absorption occurs via the excitation of electrons from occupied energy states to unoccupied ones above the Fermi energy level. Reemission takes place by decay electron transitions in the reverse direction. The perceived color of a metal is determined by the spectral composition of the reflected light.

Atomic and Electronic Interactions

Refraction

Light radiation experiences refraction in transparent materials; that is, its velocity is retarded and the light beam is bent at the interface. Index of refraction is the ratio of the velocity of light in a vacuum to that in the particular medium. The phenomenon of refraction is a consequence of electronic polarization of the atoms or ions, which is induced by the electric field component of the light wave.

Reflection

When light passes from one transparent medium to another having a different index of refraction, some of it is reflected at the interface. The degree of the reflectance depends on the indices of refraction of both media, as well as the angle of incidence.

Absorption

Nonmetallic materials are either intrinsically transparent or opaque. Opacity results in relatively narrow-band gap materials as a result of absorption whereby a photon's energy is sufficient to promote valence band-conduction band electron transitions. Transparent nonmetals have band gaps greater than about 3 eV. Some light absorption occurs in even transparent materials as a consequence of electronic polarization.

Color

For wide-band gap insulators that contain impurities, decay processes involving excited electrons to states within the band gap are possible with the emission of photons having energies less than the band gap energy. These materials appear colored, and the color depends on the distribution of wavelength ranges in the transmitted beam.

Opacity and Translucency in Insulators

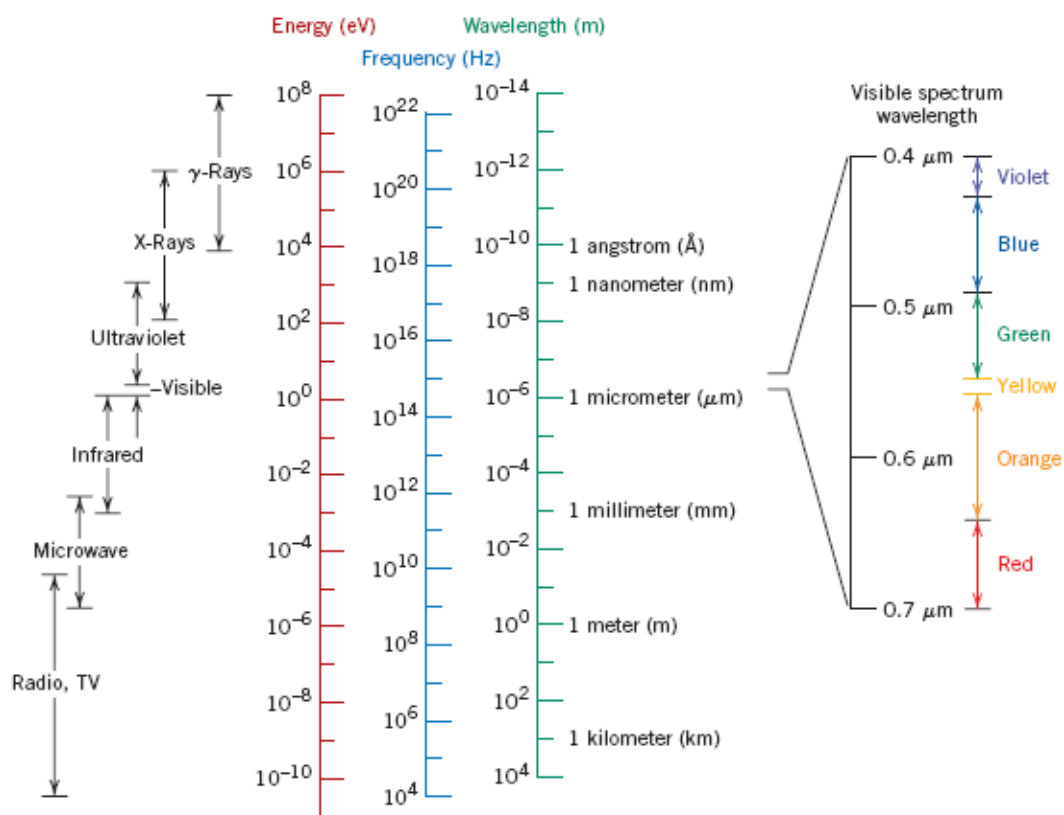
Normally transparent materials may be made translucent or even opaque if the incident light beam experiences interior reflection and/or refraction. Translucency and opacity as a result of internal scattering may occur, (1) in polycrystalline materials that have an anisotropic index of refraction, (2) in two-phase materials, (3) in materials containing small pores, and (4) in highly crystalline polymers.

Luminescence

Photoconductivity

Lasers

Three other important optical phenomena were discussed: luminescence, photoconductivity, and light amplification by stimulated emission of radiation (lasers). With luminescence, energy is absorbed as a consequence of electron excitations, which is reemitted as visible light. The electrical conductivity of some semiconductors may be enhanced by photoinduced electron transitions, whereby additional free electrons and holes are generated. Coherent and high-intensity light beams are produced in lasers by stimulated electron transitions.



The spectrum of electromagnetic radiation, including wavelength ranges for the various colors in the visible spectrum.

REFERENCES

Ashby, M. F. and D. R. H. Jones, *Engineering Materials 1, An Introduction to Their Properties and Applications*, 3rd edition, Butterworth-Heinemann, Woburn, UK, 2005.

Askeland, D. R. and P. P. Phulé, *The Science and Engineering of Materials*, 5th edition, Nelson (a division of Thomson Canada), Toronto, 2006.

Baillie, C. and L. Vanasupa, *Navigating the Materials World*, Academic Press, San Diego, CA, 2003.

Flinn, R. A. and P. K. Trojan, *Engineering Materials and Their Applications*, 4th edition, John Wiley & Sons, New York, 1994.

Smith, W. F. and J. Hashemi, *Principles of Materials Science and Engineering*, 4th edition, McGraw-Hill Book Company, New York, 2006.