Electrical behavior

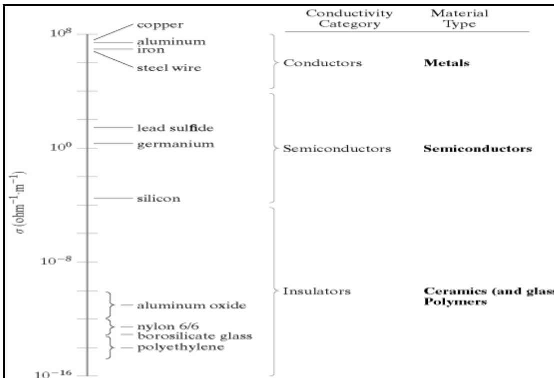
Topic 3

Reading assignment

- Chung, Multifunctional cement-based Materials, Ch. 2.
- Askeland and Phule, The Science and Engineering of Materials, 4th Ed., Chapter 18.

Supplementary reading

Shackelford, Materials Science for Engineers, 6th Ed., Ch. 15.



Conducting range	Material	Conductivity, σ ($\Omega^{-1}\cdot m^{-1}$)
Conductors	Aluminum (annealed)	35.36×10^{6}
	Copper (annealed standard)	58.00×10^{6}
	Iron (99.99 + %)	10.30×10^{6}
	Steel (wire)	$5.71–9.35 \times 10^{6}$
Semiconductors	Germanium (high purity)	2.0
	Silicon (high purity)	0.40×10^{-3}
	Lead sulfide (high purity)	38.4
Insulators	Aluminum oxide	$10^{-10}–10^{-12}$
	Borosilicate glass	10^{-13}
	Polyethylene	$10^{-13}–10^{-15}$
	Nylon 66	$10^{-12}–10^{-13}$

Source: Data from C. A. Harper, Ed., *Handbook of Materials and Processes for Electronics*, McGraw-Hill Book Company, NY, 1970; and J. K. Stanley, *Electrical and Magnetic Properties of Metals*, American Society for M

TABLE 18-1 ■ ***Electrical conductivity of selected materials at T = 300 K****

Material	Conductivity (ohm^{-1} · cm^{-1})
Superconductors	
Hg, Nb_3Sn, $YBa_2Cu_3O_{7-x}$, MgB_2	Infinite (under certain conditions such as low temperatures)
Metals	
Alkali metals:	
Na	2.13×10^{5}
K	1.64×10^{5}
Alkali earth metals:	
Mg	2.25×10^{5}
Ca	3.16×10^{5}
Group 3B metals:	
Al	3.77×10^{5}
Ga	0.66×10^{5}
Transition metals:	
Fe	1.00×10^{5}
Ni	1.46×10^{5}
Group 1B metals:	
Cu	5.98×10^{5}
Ag	6.80×10^{5}
Au	4.26×10^{5}

Material	Conductivity ($ohm^{-1} \cdot cm^{-1}$)
Semiconductors	
Group 4B elements:	
Si	5×10^{-6}
Ge	0.02
α-Sn	0.9×10^{5}
Compound semiconductors	
GaAs	2.5×10^{-9}
AlAs	0.1
SiC	10^{-10}
Ionic Conductors	
Indium tin oxide (*ITO*)	
Yttria-stabilized zirconia (*YSZ*)	
Insulators, Linear and Nonlinear Dielectrics	
Polymers:	
Polyethylene	10^{-15}
Polytetrafluorethylene	10^{-18}
Polystyrene	10^{-17} to 10^{-19}
Epoxy	10^{-12} to 10^{-17}
Ceramics:	
Alumina (Al_2O_3)	10^{-14}
Silicate glasses	10^{-17}
Boron nitride (BN)	10^{-13}
Barium titanate ($BaTiO_3$)	10^{-14}
C (diamond)	$<10^{-18}$

* *Unless specified otherwise, assumes high purity material.*

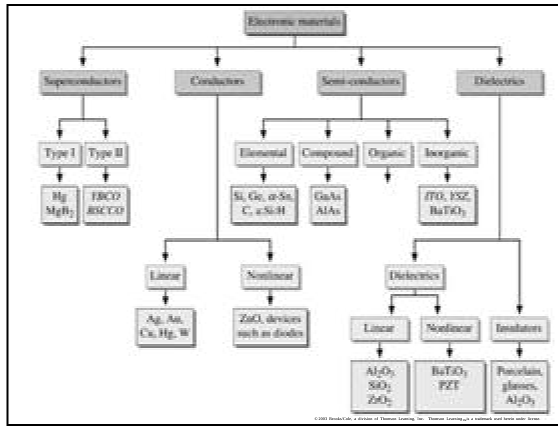
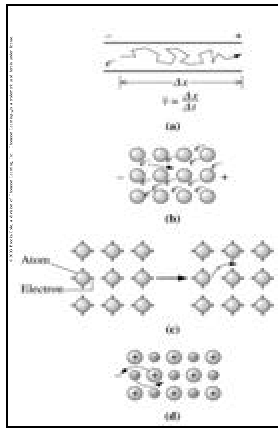
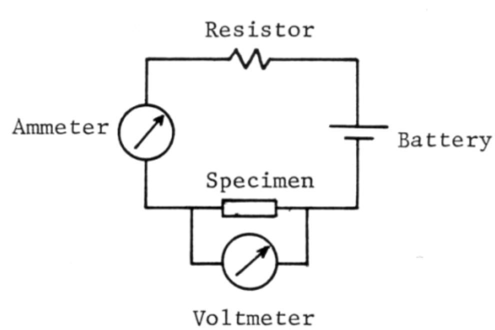


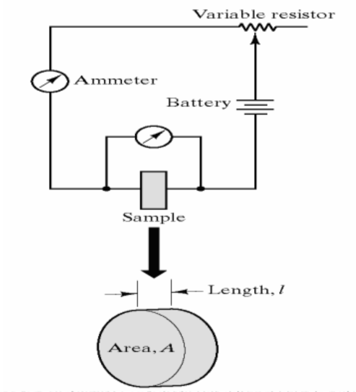
Figure 18.2 (a) Charge carriers, such as electrons, are deflected by atoms or defects and take an irregular path through a conductor. The average rate at which the carriers move is the drift velocity v. (b) Valence electrons in the metallic bond move easily. (c) Covalent bonds must be broken in semiconductors and insulators for an electron to be able to move. (d) Entire ions must diffuse to carry charge in many ionically bonded materials.

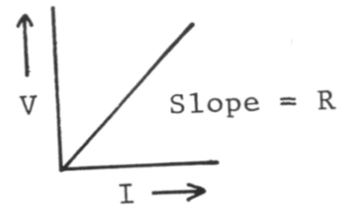


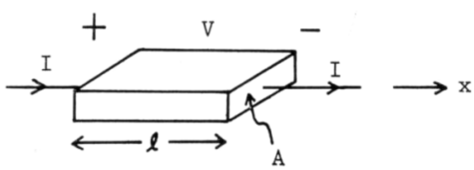
Mean free path –

The average distance that electrons can move without being scattered by other atoms.









Current

$$I = \frac{\text{charge}}{\text{time}}.$$

$$1 \text{ ampere} = \frac{1 \text{ coulomb}}{\text{sec}}.$$

Current density

$$\tilde{J} = \frac{I}{A}$$

TABLE 18-2 ■ *Some useful relationships, constants, and units*

Electron volt = 1 eV = 1.6 × 10^{-19} Joule = 1.6 × 10^{-12} erg
1 amp = 1 coulomb/second
1 volt = 1 amp · ohm
$k_B T$ at room temperature (300 K) = 0.0259 eV
c = speed of light 2.998 × 10^{-8} m/s
ε_0 = perimitivity of free space = 8.85 × 10^{-12} F/m
q = charge on electron = 1.6 × 10^{-19} C
Avogadro's number N_A = 6.023 × 10^{23}
k_B = Boltzmann's constant = 8.63 × 10^{-5} eV/K = 1.38 × 10^{-23} J/K
h = Planck's constant 6.63 × 10^{-34} J-s = 4.14 × 10^{-15} eV-s

Current density –

The current flowing through per unit cross-sectional area.

Electrical resistance

$$R \propto \frac{\ell}{A}$$

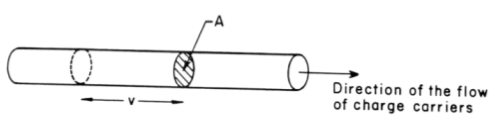
$$R = \frac{1}{s}\frac{\ell}{A}$$

where s is the electrical conductivity

$$R = \frac{V}{I}$$

$$s = \frac{\ell}{A}\frac{I}{V} = \frac{(I/A)}{(V/\ell)}$$

$$s = \frac{\tilde{J}}{(V/\ell)}$$



Electric field –

The voltage gradient or volts per unit length.

$$\frac{dV}{dx} = -\frac{V}{\ell}$$

Electric field

$$E = -\frac{dV}{dx}$$

$$\frac{V}{\ell} = -\frac{dV}{dx} = E$$

$$s = \frac{\tilde{J}}{E}$$

Drift velocity

$$v \propto E$$

$$v = \mu E$$

where μ is the mobility

- **Drift velocity - The average rate at which electrons or other charge carriers move through a material under the influence of an electric or magnetic field.**
- **Mobility - The ease with which a charge carrier moves through a material.**

- Current density - The current flowing through per unit cross-sectional area.
- Electric field - The voltage gradient or volts per unit length.
- Drift velocity - The average rate at which electrons or other charge carriers move through a material under the influence of an electric or magnetic field.
- Mobility - The ease with which a charge carrier moves through a material.
- Dielectric constant - The ratio of the permittivity of a material to the permittivity of a vacuum, thus describing the relative ability of a material to polarize and store a charge; the same as relative permittivity.

$$I = qnvA$$

$$\tilde{J} = \frac{I}{A} = \frac{qnvA}{A} = qnv$$

$$s = \frac{\tilde{J}}{E} = \frac{qnv}{E}$$

$$\frac{v}{E} = m$$

$$\sigma = q\,n\,\mu$$

Flux

$$J_n = -D_n \frac{dn}{dx}$$

Current density

$$\tilde{J}_n = (-q)\,J_n$$

$$\tilde{J}_n = (-q)\left(-D_n \frac{dn}{dx}\right)$$

$$= q\,D_n \frac{dn}{dx}\ .$$

Flux

$$J_p = -D_p \frac{dp}{dx}$$

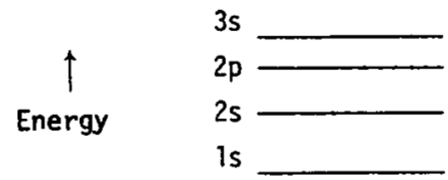
Current density

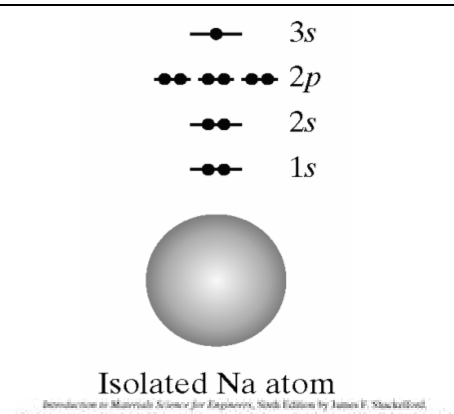
$$\tilde{J}_p = q\,J_p = q\left(-D_p \frac{dp}{dx}\right) = -q\,D_p \frac{dp}{dx}\ .$$

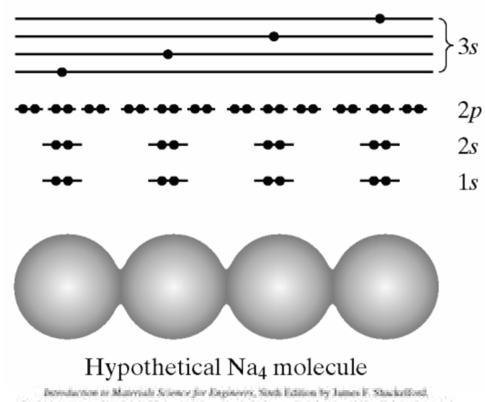
Einstein relationship

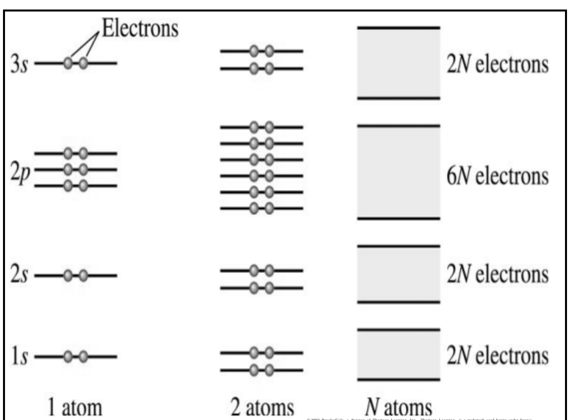
$$\frac{D_n}{m_n} = \frac{D_p}{m_p} = \frac{kT}{q}$$

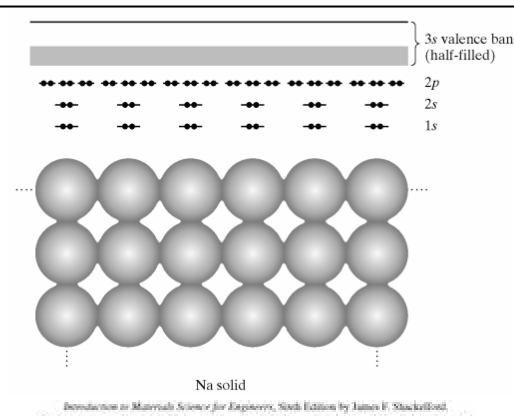
Energy levels of an isolated atom



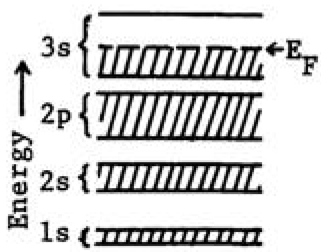


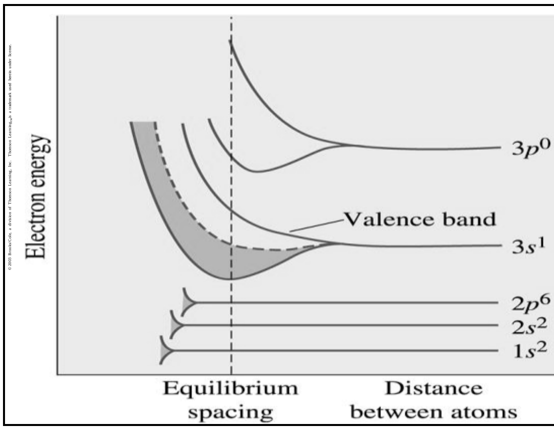


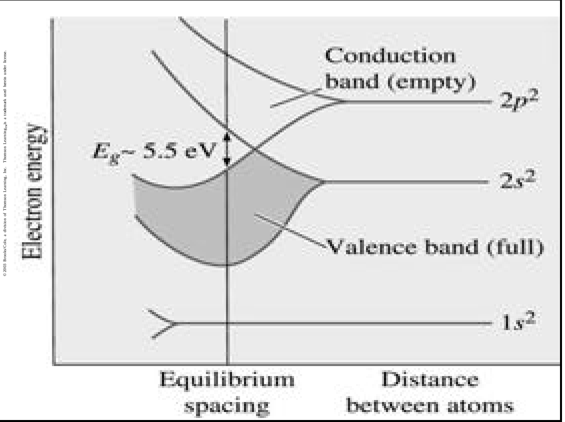




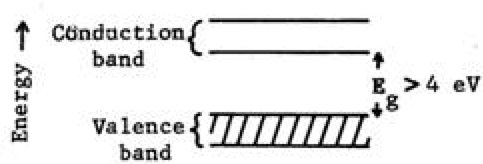
Energy bands of solid sodium



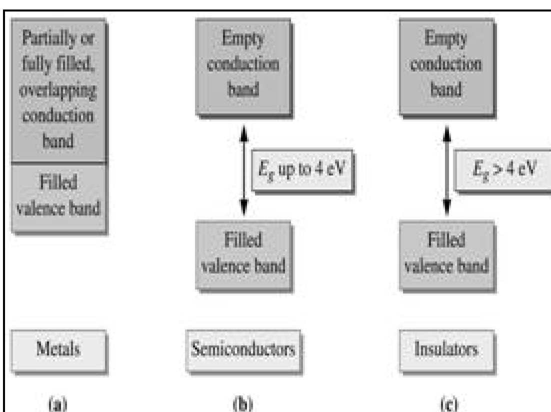




Energy bands of an insulator



- **Valence band - The energy levels filled by electrons in their lowest energy states.**
- **Conduction band - The unfilled energy levels into which electrons can be excited to provide conductivity.**
- **Energy gap (Bandgap) - The energy between the top of the valence band and the bottom of the conduction band that a charge carrier must obtain before it can transfer a charge.**



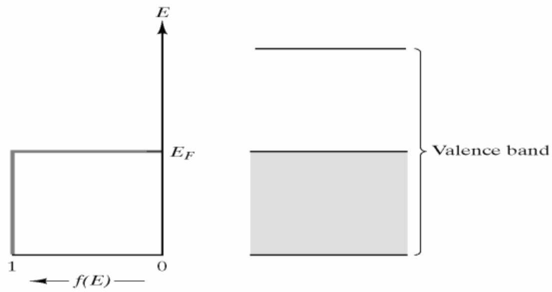


Figure 15.5

The Fermi function, $f(E)$, describes the relative filling of energy levels. At 0 K, all energy levels are completely filled up to the Fermilevel, E_F, and are completely empty above E_F.

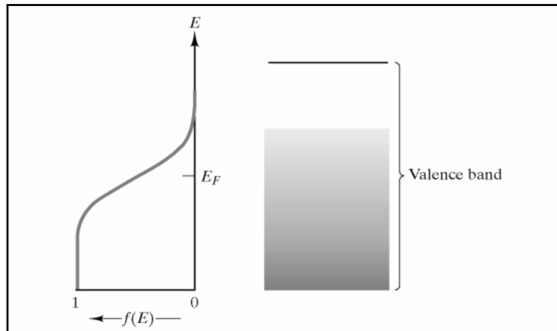


Figure 15.6

At $T > 0$ K, the Fermi function, $f(E)$, indicates promotion of some electrons above E_F.

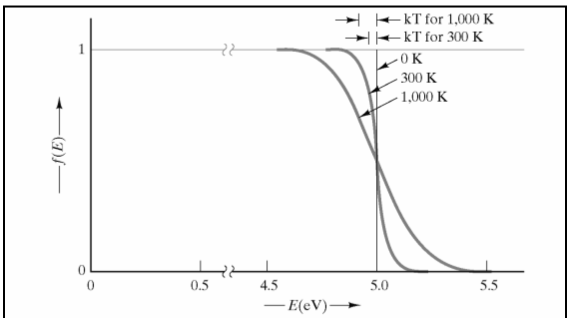


Figure 15.7

Variation of the Fermi function, $f(E)$, with the temperature for a typical metal (with E_F = 5 eV). Note that the energy range over which $f(E)$ drops from 1 to 0 is equal to a few times kT.

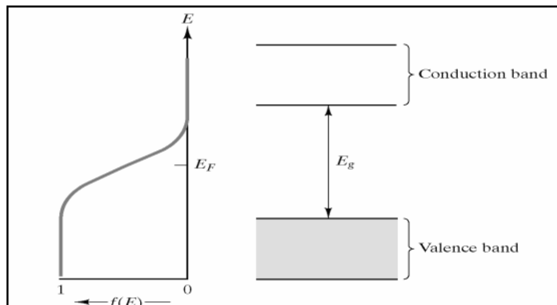


Figure 15.8

Comparison of the Fermi function, $f(E)$, with the energy band structure for an insulator. Virtually no electrons are promoted to the conduction band [$f(E) = 0$ there] because of the magnitude of the band gap (> 2 eV).

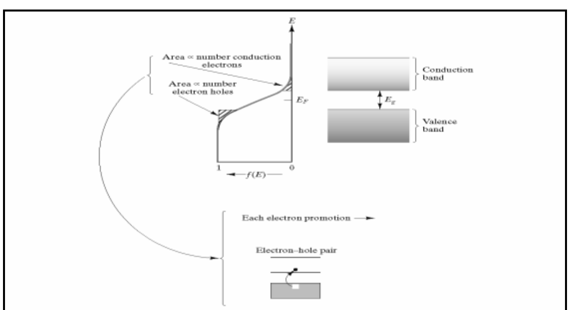
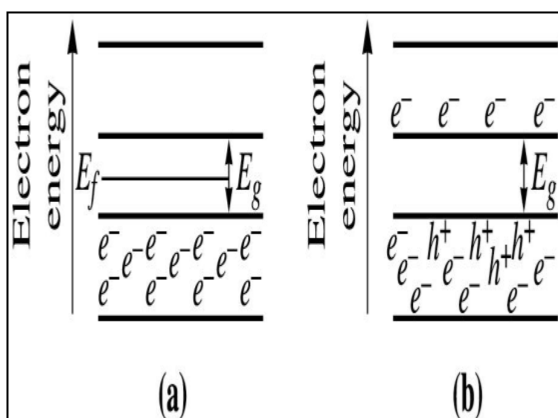


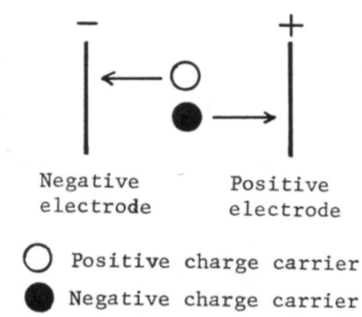
Figure 15.9

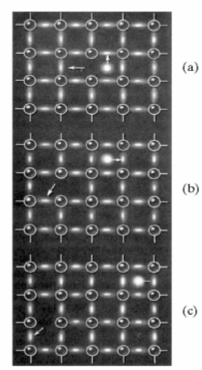
Comparison of the Fermi function, $f(E)$, with the energy band structure for a semiconductor. A significant number of electrons is promoted to the conduction band because of a relatively small band gap (< 2 eV). Each electron promotion creates a pair of charge carriers (i.e., an electron-hole pair).



- **Holes are in the valence band.**
- **Conduction electrons are in the conduction band.**

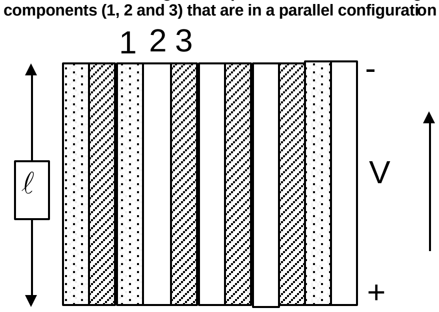
Holes - Unfilled energy levels in the valence band. Because electrons move to fill these holes, the holes move and produce a current.





Radiative recombination - Recombination of holes and electrons that leads to emission of light; this occurs in direct bandgap materials.

Electrical conduction through a composite material consisting of three components (1, 2 and 3) that are in a parallel configuration



Resistance due to component i

$$R_i = r_i \frac{\ell}{A_i}$$

Current through component i

$$I_i = \frac{VA_i}{r_i \ell}$$

Total current through the composite

$$I = I_1 + I_2 + I_3 = \frac{V}{\ell}\left(\frac{A_1}{r_1} + \frac{A_2}{r_2} + \frac{A_3}{r_3}\right)$$

Total resistance

$$R = r_{||}\frac{\ell}{\left(A_1 + A_2 + A_3\right)}$$

Total current

$$I = \frac{V}{R} = \frac{V\left(A_1 + A_2 + A_3\right)}{r_{||}\ell}$$

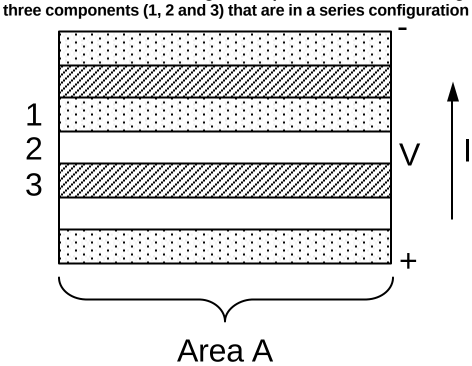
$$\frac{V}{\ell}\left(\frac{A_1}{r_1} + \frac{A_2}{r_2} + \frac{A_3}{r_3}\right) = \frac{V}{r_{||}\ell}\left(A_1 + A_2 + A_3\right)$$

$$\frac{1}{r_{||}} = \frac{1}{r_1}\frac{A_1}{\left(A_1 + A_2 + A_3\right)} + \frac{1}{r_2}\frac{A_2}{\left(A_1 + A_2 + A_3\right)} + \frac{1}{r_3}\frac{A_3}{\left(A_1 + A_2 + A_3\right)}$$

$$= \frac{1}{r_1}f_1 + \frac{1}{r_2}f_2 + \frac{1}{r_3}f_3,$$

Rule of Mixtures

Electrical conduction through a composite material consisting of three components (1, 2 and 3) that are in a series configuration



$$V_i = IR_i$$

$$= Ir_i \frac{L_i}{A}$$

Total voltage drop

$$V = \frac{I}{A}\left(r_1 L_1 + r_2 L_2 + r_3 L_3\right)$$

Total resistance

$$R = r_{\perp}\frac{\left(L_1 + L_2 + L_3\right)}{A}$$

Total voltage drop

$$V = IR$$

$$= Ir_{\perp}\frac{\left(L_1 + L_2 + L_3\right)}{A}$$

Total voltage drop

$$V = \frac{I}{A}\left(r_1 L_1 + r_2 L_2 + r_3 L_3\right)$$

$$V = IR$$

$$= I r_\perp \frac{\left(L_1 + L_2 + L_3\right)}{A}$$

$$\frac{I}{A}\left(r_1 L_1 + r_2 L_2 + r_3 L_3\right)$$

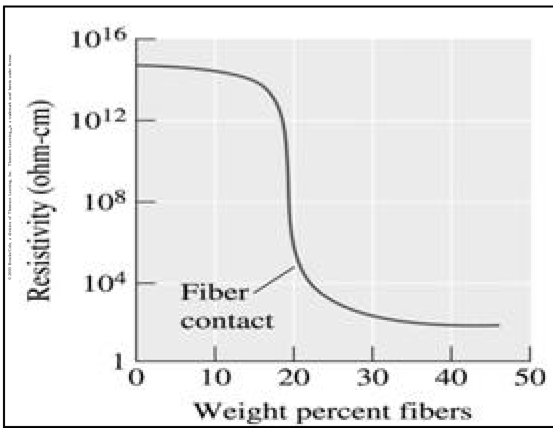
$$= I r_\perp \frac{\left(L_1 + L_2 + L_3\right)}{A}$$

$$r_\perp = \frac{\left(r_1 L_1 + r_2 L_2 + r_3 L_3\right)}{\left(L_1 + L_2 + L_3\right)}$$

$$= ?_1 f_1 + ?_2 f_2 + ?_3 f_3$$

Rule of Mixtures

Conduction through a composite material with an insulating matrix and short conductive fibers



Percolation threshold

Minimum volume fraction of conductive fibers (or particles) for adjacent fibers (or particles) to touch each other and form a continuous conductive path.

Conduction through an interface

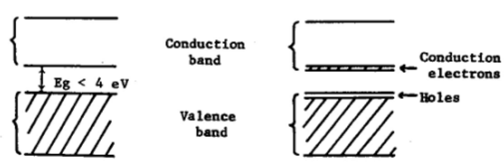
Contact resistance

$$R_c \propto \frac{1}{A}$$

$$R_c = \frac{\rho_c}{A}$$

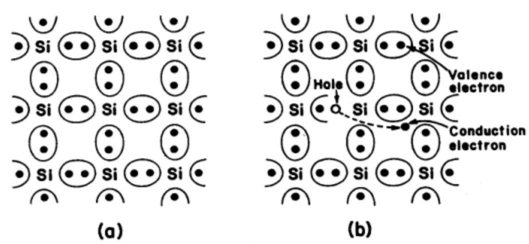
where ?c is the contact resistivity

Energy bands of an intrinsic semiconductor



(a) **Without thermal excitation** (b) **With thermal excitation**

Intrinsic silicon



Without thermal excitation **With thermal excitation**

Electrical conductivity of a semiconductor

$$\sigma = qn\mu_n + qp\mu_p \ ,$$

where q = magnitude of the charge of an electron,
n = number of conduction electrons per unit volume,
p = number of holes per unit volume,
μ_n = mobility of conduction electrons,
and μ_p = mobility of conduction holes.

For an intrinsic semiconductor (n = p),

$$\sigma = qn(\mu_n + \mu_p) \ .$$

Current density due to both an electric field and a concentration gradient

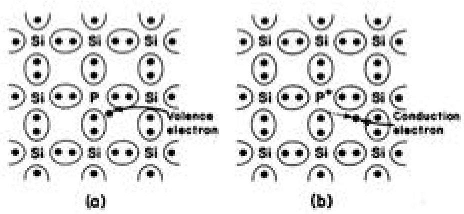
$$\tilde{J}_n = qn\,\mu_n E + qD_n \frac{dn}{dx} \; .$$

$$\tilde{J}_p = qp\,\mu_p E - qD_p \frac{dp}{dx} \; .$$

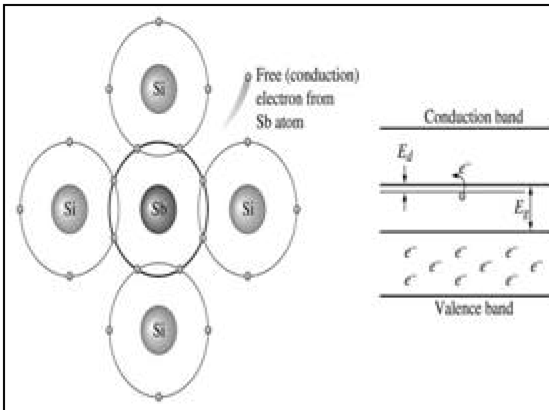
$$\tilde{J} = \tilde{J}_n + \tilde{J}_p \; .$$

- Intrinsic semiconductor - A semiconductor in which properties are controlled by the element or compound that makes the semiconductor and not by dopants or impurities.
- Extrinsic semiconductor - A semiconductor prepared by adding dopants, which determine the number and type of charge carriers.
- Doping - Deliberate addition of controlled amounts of other elements to increase the number of charge carriers in a semiconductor.

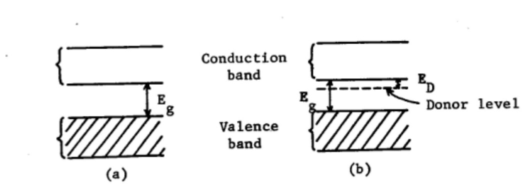
Extrinsic semiconductor (doped with an electron donor)



Without thermal excitation **With thermal excitation**

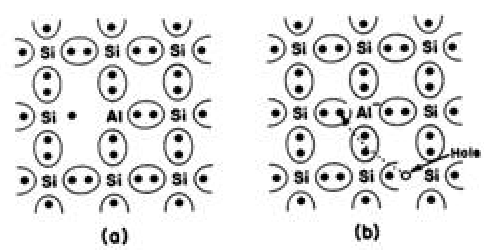


Energy bands

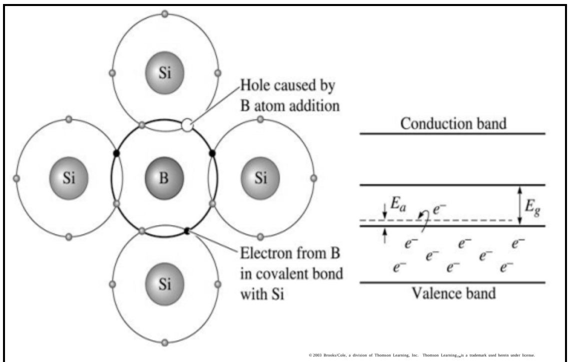


Intrinsic semiconductor **Extrinsic semiconductor (doped with an electron donor)**

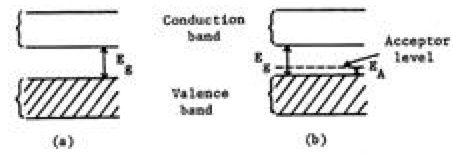
Extrinsic semiconductor (doped with an electron acceptor)



Without thermal excitation **With thermal excitation**



Energy bands



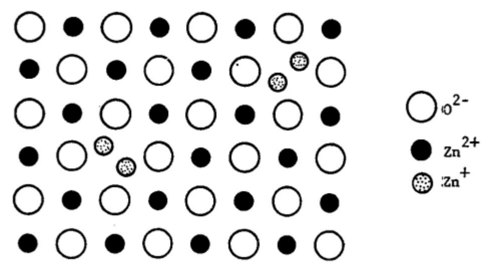
Intrinsic semiconductor

Extrinsic semiconductor (doped with an electron acceptor)

TABLE 18-7 *The donor and acceptor energy gaps (in electron volts) when silicon and germanium semiconductors are doped*

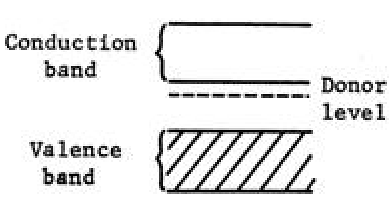
	Silicon		Germanium	
Dopant	E_d	E_a	E_d	E_a
P	0.045		0.0120	
As	0.049		0.0127	
Sb	0.039		0.0096	
B		0.045		0.0104
Al		0.057		0.0102
Ga		0.065		0.0108
In		0.160		0.0112

Defect semiconductor
(excess semiconductor $Zn_{1+x}O$)

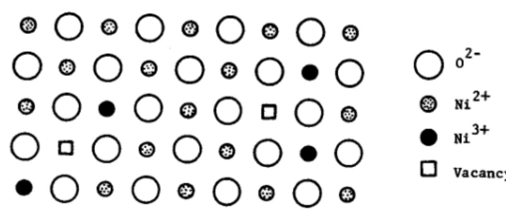


Zn^{+} ion serves as an electron donor.

Energy bands of $Zn_{1+x}O$

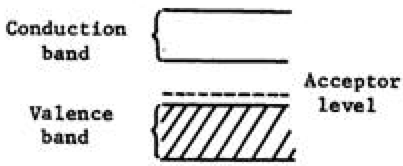


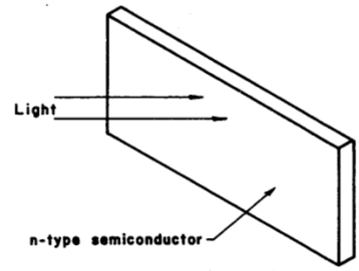
Defect semiconductor
(deficit semiconductor $Ni_{1-x}O$)



Ni^{3+} ion serves as an electron acceptor.

Energy bands of $Ni_{1-x}O$





$$n = \frac{c}{l}$$

$$E \propto n$$

$$E = hn$$ **(Photon energy)**

where h = Planck's constant

= 6.6262 x 10^{-34} J.s

Photon energy must be at least equal to the energy bandgap in order for electrons to be excited from the valence band to the conduction band.

Consider an n-type semiconductor being illuminated.

Illumination increases conduction electrons and holes by equal number, since electrons and holes are generated in pairs.

Thus, the minority carrier concentration (p_n) is affected much more than the majority carrier concentration (n_n).

Material	Energy gap, E_g (eV)	Electron mobility, $\mu_e[m^2/(V \cdot s)]$	Hole mobility, $\mu_h[m^2/(V \cdot s)]$	Carrier density, $n_e(= n_h)$ (m^{-3})
Si	1.107	0.140	0.038	14×10^{15}
Ge	0.66	0.364	0.190	23×10^{18}
CdS	2.59[a]	0.034	0.0018	—
GaAs	1.47	0.720	0.020	1.4×10^{12}
InSb	0.17	8.00	0.045	13.5×10^{21}

Source: Data from C. A. Harper, Ed., *Handbook of Materials and Processes for Electronics*, McGraw-Hill Book Company, NY, 1970.

[a] This value is above our upper limit of 2 eV used to define a semiconductor. Such a limit is somewhat arbitrary. In addition, most commercial devices involve impurity levels that substantially change the nature of the band gap (see Chapter 17).

Table 15.5

Properties of Some Common Semiconductors at Room Temperature (300 K).

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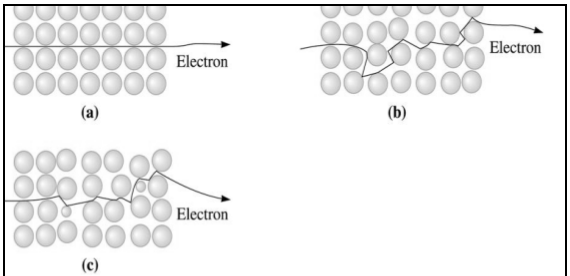
ISBN 0-13-1-42486-6.

Table 18-6 ■ Properties of commonly encountered semiconductors

Semiconductor	Bandgap eV	Mobility of Electrons (μ_n) $\frac{cm^2}{V\text{-}s}$	Mobility of Holes (μ_p) $\frac{cm^2}{V\text{-}s}$	Dielectric Constant (k)	Resistivity Ω-cm	Density $\frac{gm}{cm^3}$	Melting Temperature °C
Silicon (Si)	1.11	1350	480	11.8	2.5×10^5	2.33	1415
Amorphous Silicon (a:Si:H)	1.70	1	10^{-2}	~11.8	10^{10}	~2.30	—
Germanium (Ge)	0.67	3900	1900	16.0	43	5.32	936
SiC (α)	2.86	500		10.2	10^{10}	3.21	2830
Gallium Arsenide (GaAs)	1.43	8500	400	13.2	4×10^8	5.31	1238
Diamond	~5.50	1800	1500	5.7	$>10^{18}$	3.52	~4200
α-Sn	0.10	2000	1000	—	10^{-4}	5.80	232



- **Temperature Effect - When the temperature of a metal increases, thermal energy causes the atoms to vibrate**
- **Effect of Atomic Level Defects - Imperfections in crystal structures scatter electrons, reducing the mobility and conductivity of the metal**

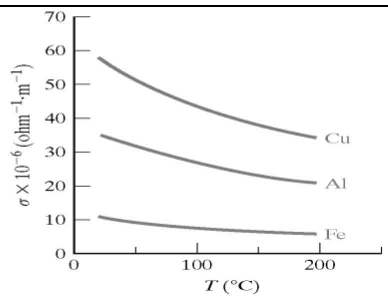


Figure 15.10

Variation in electrical conductivity with temperature for some metals. (From J. K. Stanley, Electrical and Magnetic Properties of Metals, *American Society for Metals, Metals Park, OH, 1963.)*

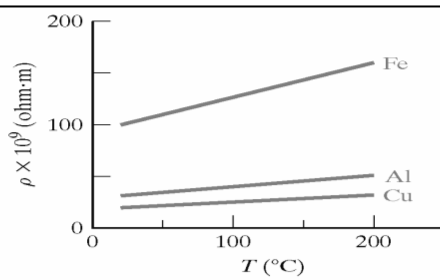


Figure 15.11

Variation in electrical resistivity with temperature for the same metals shown in Figure 15.10. The linearity of these data defines the temperature coefficient of resistivity, α.

Change of resistivity with temperature for a metal

$$\frac{\Delta r}{r} = a\,\Delta T$$

where α = temperature coefficient of electrical resistivity

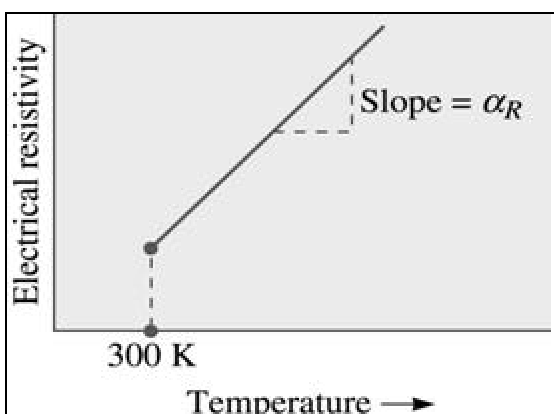


TABLE 18-3 ■ *The temperature resistivity coefficient α_R for selected metals[1]*

Metal	Room Temperature Resistivity (ohm · cm)	Temperature Resistivity Coefficient (α_R) (ohm/ohm · °C)
Be	4.0×10^{-6}	0.0250
Mg	4.45×10^{-6}	0.0037
Ca	3.91×10^{-6}	0.0042
Al	2.65×10^{-6}	0.0043
Cr	12.90×10^{-6} (0°C)	0.0030
Fe	9.71×10^{-6}	0.0065
Co	6.24×10^{-6}	0.0053
Ni	6.84×10^{-6}	0.0069
Cu	1.67×10^{-6}	0.0043
Ag	1.59×10^{-6}	0.0041
Au	2.35×10^{-6}	0.0035
Pd	10.8×10^{-6}	0.0037
W	5.3×10^{-6} (27°C)	0.0045
Pt	9.85×10^{-6}	0.0039

(Source: Reprinted by permission from Handbook of Electronic Materials, by P.S. Neelakanta, pp. 215–216, Table 9-1. Copyright © 1995 CRC Press, Boca Raton, Florida.)

Material	Resistivity at 20° C ρ_{rt} ($\Omega \cdot m$)	Temperature coefficient of resistivity at 20° C α (°C^{-1})
Aluminum (annealed)	28.28×10^{-9}	0.0039
Copper (annealed standard)	17.24×10^{-9}	0.00393
Gold	24.4×10^{-9}	0.0034
Iron (99.99+%)	97.1×10^{-9}	0.00651
Lead (99.73+%)	206.48×10^{-9}	0.00336
Magnesium (99.80%)	44.6×10^{-9}	0.01784
Mercury	958×10^{-9}	0.00089
Nickel (99.95% + Co)	68.4×10^{-9}	0.0069
Nichrome (66% Ni + Cr and Fe)	$1,000 \times 10^{-9}$	0.0004
Platinum (99.99%)	106×10^{-9}	0.003923
Silver (99.78%)	15.9×10^{-9}	0.0041
Steel (wire)	$107–175 \times 10^{-9}$	0.006–0.0036
Tungsten	55.1×10^{-9}	0.0045
Zinc	59.16×10^{-9}	0.00419

Source: Data from J. K. Stanley, *Electrical and Magnetic Properties of Metals*, American Society for Metals, Metals Park, OH, 1963.

Table 15.2

Resistivities and Temperature Coefficients of Resistivity for Some Metallic Conductors.

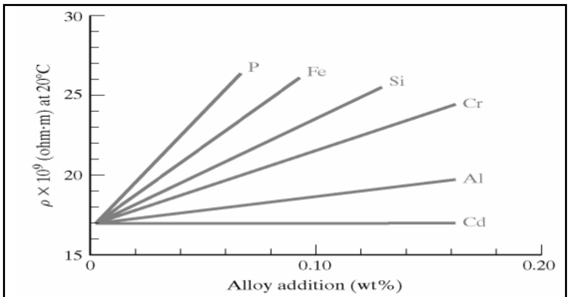
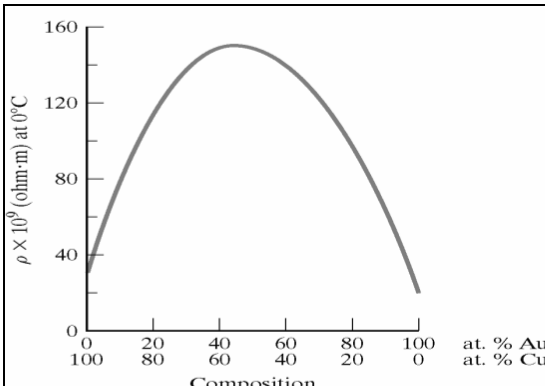
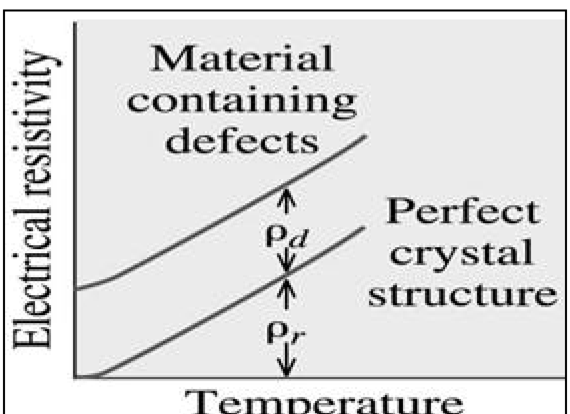


Figure 15.12

...on in electrical resistivity with composition for various copper alloys wit... ...f elemental additions. Note that all data are at a fixed temperature (20° ... ... K. Stanley, Electrical and Magnetic Properties of Metals, *American Soc... Metals Park, OH, 1963.)*

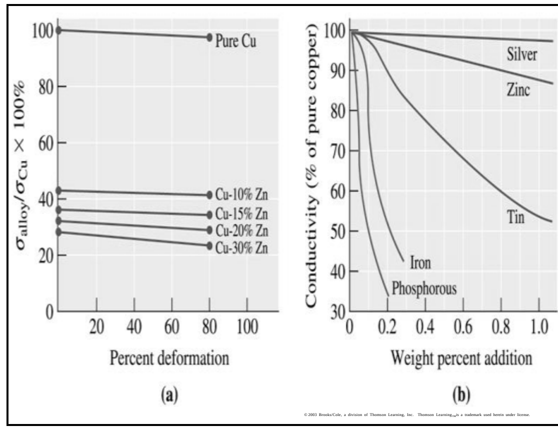




Matthiessen's rule –

The resistivity of a metallic material is given by the addition of a base resistivity that accounts for the effect of temperature, and a temperature independent term that reflects the effect of atomic level defects, including impurities forming solid solutions.

Effect of Processing and Strengthening



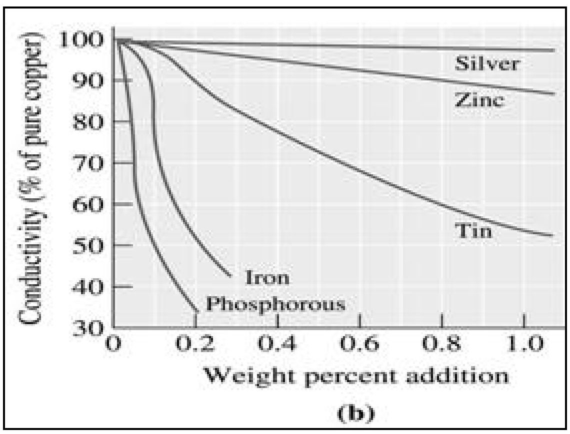
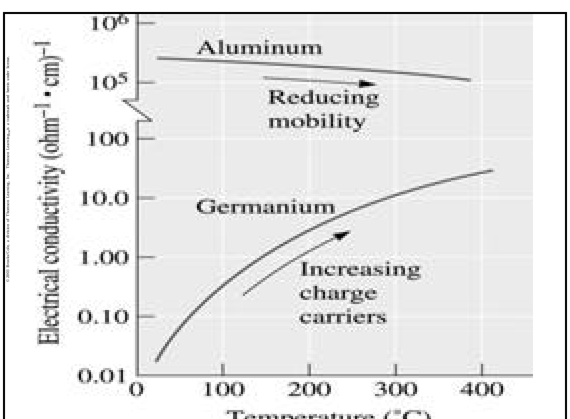


TABLE 18-4 ■ ***The effect of alloying, strengthening, and processing on the electrical conductivity of copper and its alloys***

Alloy	$\frac{\sigma_{alloy}}{\sigma_{Cu}} \times 100$	Remarks
Pure annealed copper	100	Few defects to scatter electrons; the mean free path is long.
Pure copper deformed 80%	98	Many dislocations, but because of the tangled nature of the dislocation networks, the mean free path is still long.
Dispersion-strengthened Cu-0.7% Al_2O_3	85	The dispersed phase is not as closely spaced as solid-solution atoms, nor is it coherent, as in age hardening. Thus, the effect on conductivity is small.
Solution-treated Cu-2% Be	18	The alloy is single phase; however, the small amount of solid-solution strengthening from the supersaturated beryllium greatly decreases conductivity.
Aged Cu-2% Be	23	During aging, the beryllium leaves the copper lattice to produce a coherent precipitate. The precipitate does not interfere with conductivity as much as the solid-solution atoms.
Cu-35% Zn	28	This alloy is solid-solution strengthened by zinc, which has an atomic radius near that of copper. The conductivity is low, but not as low as when beryllium is present.



s **= q n** m

For a metal, s decreases with increasing temperature because μ decreases with increasing temperature.

For a semiconductor, s increases with increasing temperature because n and/or p increases with increasing temperature.

For a semiconductor

$$n \propto e^{-E_g/2kT} ,$$

where E_g = energy band gap between conduction and valence bands,
k = Boltzmann's constant,
and T = temperature in K.

The factor of 2 in the exponent is because the excitation of an electron across E_g produces an intrinsic conduction electron and an intrinsic hole.

Taking natural logarithms,

$$s = s_o e^{-E_g/2kT} .$$

$$\ln s = \ln s_o - \frac{E_g}{2kT} .$$

Changing the natural logarithms to logarithms of base 10,

$$\log s = \log s_o - \frac{E_g}{(2.3)2kT} .$$

Thermistor –

A semiconductor device that is particularly sensitive to changes in temperature, permitting it to serve as an accurate measure of temperature.

Conductivity of an ionic solid

$$s = qn m_C + qn m_A = qn(m_C + m_A) ,$$

where n = number of Schottky defects per unit volume
μ_C = mobility of cations,
μ_A = mobility of anions.

An n-type semiconductor

$$n = n_i + n_e ,$$

where n = total concentration of conduction electrons,
n_i = concentration of intrinsic conduction electrons,
n_e = concentration of extrinsic conduction electrons.

$$D \rightarrow D^+ + e^- ,$$

$$n_e = N_D{}^+ ,$$

$$n_i \propto e^{-Eg/2kT} .$$

$$n_e \propto e^{-E_D/kT} .$$

$$n_i << n_e .$$

$$p = p_i .$$

Before donor exhaustion

$$n_i << n_e \quad .$$

No extrinsic holes, thus

$$p = p_i \quad .$$

However,

$$p_i = n_i$$

Thus,

$$p = n_i$$

$$n \cong n_e$$
$$p \cong 0 \quad .$$

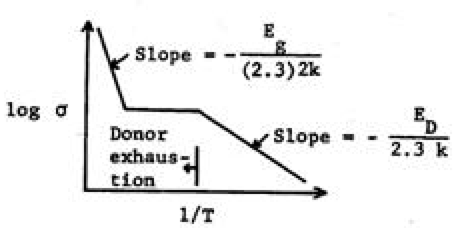
$$s = qn\, m_n + qp\, m_p \quad .$$

$$s \cong qn\, m_n$$

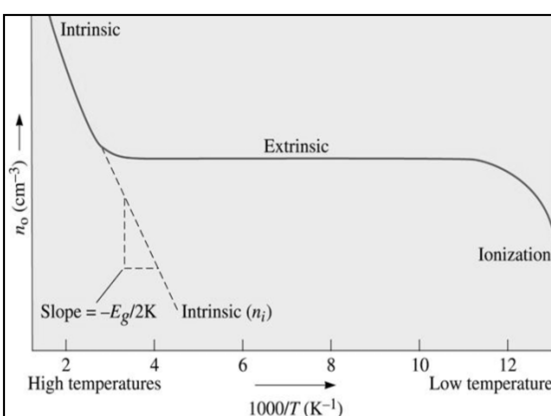
At high temperatures (i.e., donor exhaustion),

$$n \cong n_i$$

Arrhenius plot of log conductivity vs. 1/T, where T is temperature in K.



Extrinsic semiconductor (doped with an electron donor)

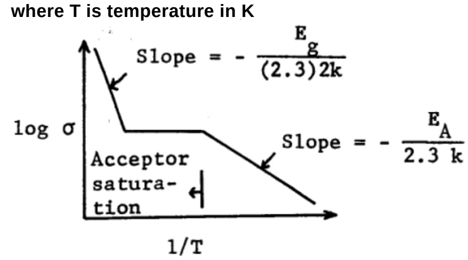


A p-type semiconductor

$$p = p_i + p_e \quad ,$$

where p = total concentration of conduction holes
p_i = concentration of intrinsic holes,
p_e = concentration of extrinsic holes.

Arrhenius plot of log conductivity vs. 1/T, where T is temperature in K



Extrinsic semiconductor
(doped with an electron acceptor)

$$A + e^- \rightarrow A^- \quad ,$$

$$A \rightarrow A^- + h^+ \quad ,$$

$$p_e = N_{A^-} \quad ,$$

$$p_i \propto e^{-Eg/2kT} \quad ,$$

$$p_e \propto e^{-EA/kT} \quad .$$

$$p_i << p_e$$

before acceptor saturation

$$n = n_i \quad .$$

$$n = p_i \quad .$$

$$p \cong p_e$$

$$n \cong 0 \quad .$$

before acceptor saturation

The mass-action law

Product of n and p is a constant for a particular semiconductor at a particular temperature

Intrinsic semiconductor

$$n = n_i = p_i = p \quad .$$

$$np = n_i^2 \quad .$$

$$n_i = 1.5\times10^{10}\,\text{cm}^{-3} \text{ for Si}$$

$$n_i = 2.5\times10^{13}\,\text{cm}^{-3} \text{ for Ge} \quad .$$

This equation applies whether the semiconductor is doped or not.

Consider an n-type semiconductor.

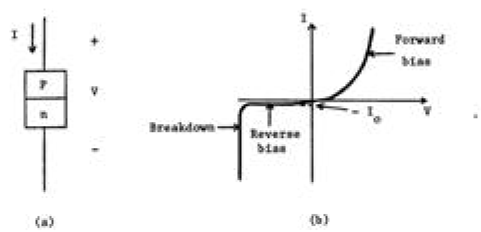
$$n \cong n_e = N_{D+}$$

$$N_{D+} = N_D \quad \textbf{(Donor exhaustion)}$$

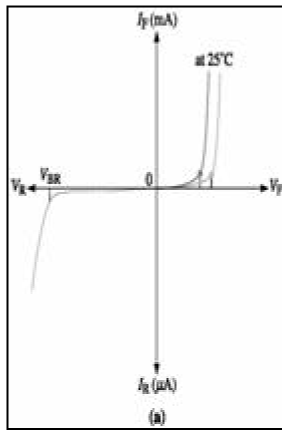
$$n \cong N_D \quad .$$

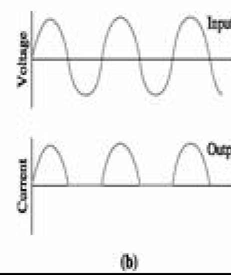
$$p = \frac{n_i^2}{n} = \frac{n_i^2}{N_D} \quad .$$

The pn junction

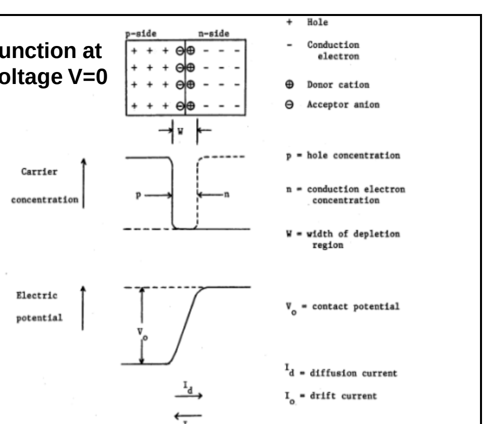


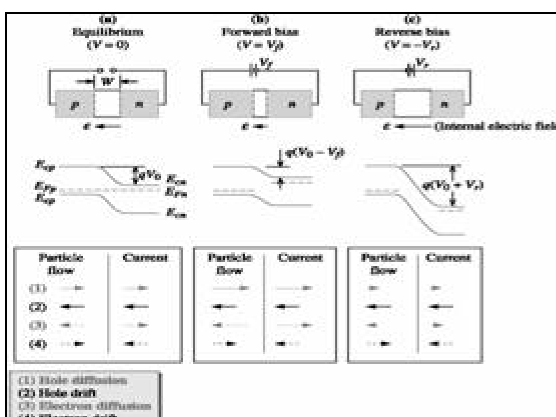
Rectification





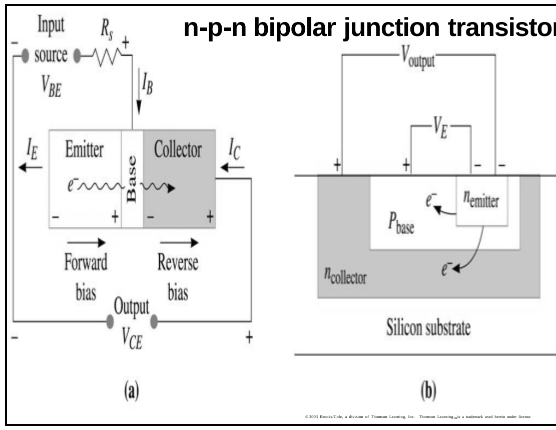
A pn junction at bias voltage V=0



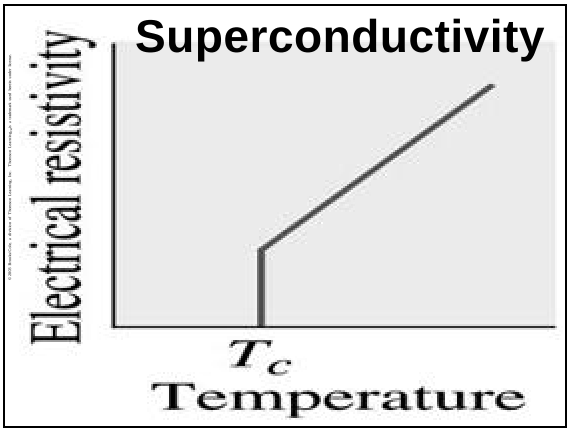


- Diodes, transistors, lasers, and LEDs are made using semiconductors. Silicon is the workhorse of very large scale integrated (VLSI) circuits.
- Forward bias - Connecting a *p-n* junction device so that the *p*-side is connected to positive. Enhanced diffusion occurs as the energy barrier is lowered, permitting a considerable amount of current can flow under forward bias.
- Reverse bias - Connecting a junction device so that the *p*-side is connected to a negative terminal; very little current flows through a *p-n* junction under reverse bias.
- Avalanche breakdown - The reverse-bias voltage that causes a large current flow in a lightly doped *p-n* junction.
- Transistor - A semiconductor device that can be used to amplify electrical signals.

n-p-n bipolar junction transistor



Superconductivity



- Superconductivity - Flow of current through a material that has no resistance to that flow.
- Applications of Superconductors - Electronic circuits have also been built using superconductors and powerful superconducting electromagnets are used in magnetic resonance imaging (MRI). Also, very low electrical-loss components, known as filters, based on ceramic superconductors have been developed for wireless communications.

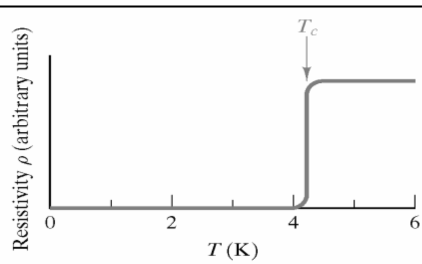


Figure 15.16

Resistivity of mercury drops suddenly to zero at a critical temperature, T_C (= 4.12 K). Below T_c, mercury is a superconductor.

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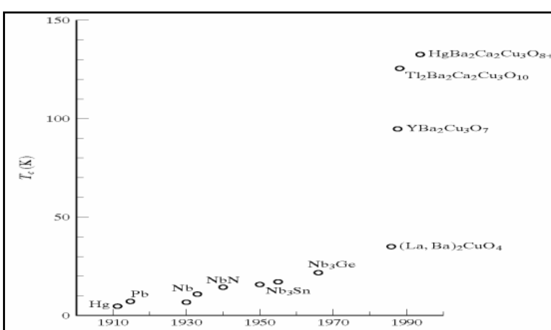

Figure 15.17

The highest value of T_c increased steadily with time until the development of ceramic-oxide superconductors in 1986.

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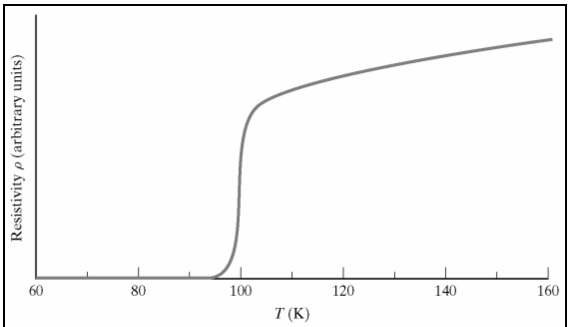

Figure 15.18

The resistivity of $YBa_2Cu_3O_7$ as a function of temperature, indicating a $T_c \approx 95$ K.

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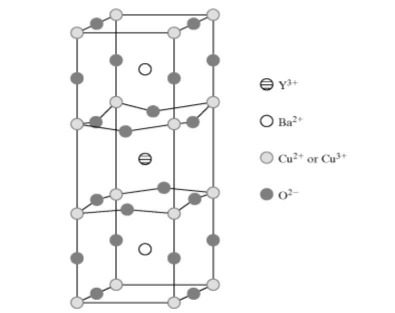

Figure 15.19

Unit cell of $YBa_2tCu_3O_7$. It is roughly equivalent to three distorted perovskite unit cells of the type shown in Figure 3.14.

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