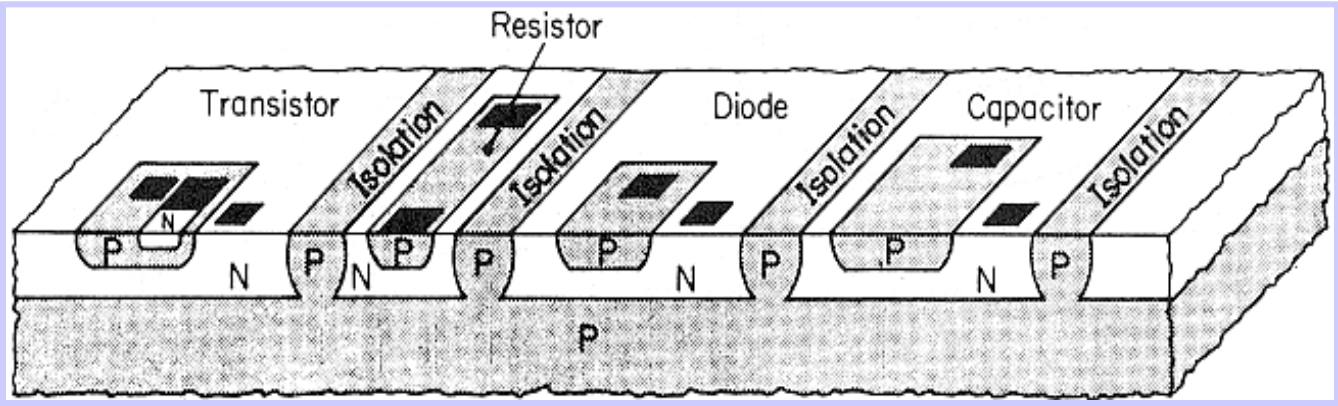
CHAPTER 18: ELECTRICAL PROPERTIES

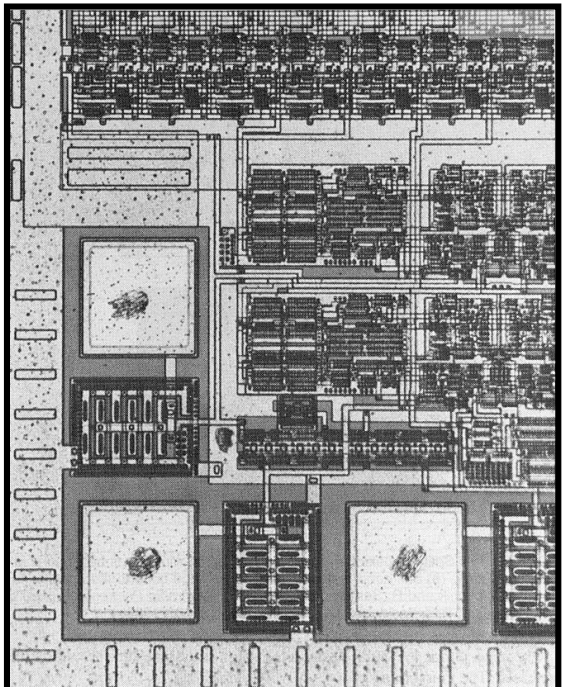
- Electrical Conduction
- Mobility
- Conductor
- Ionic Materials
- Conducting Polymer
- Amorphous Materials
- Semiconductor
- Dielectrics

INTRODUCTION

• electrical properties of materials is important when selecting a material for integrated circuits, transistor, semiconductor or insulator.



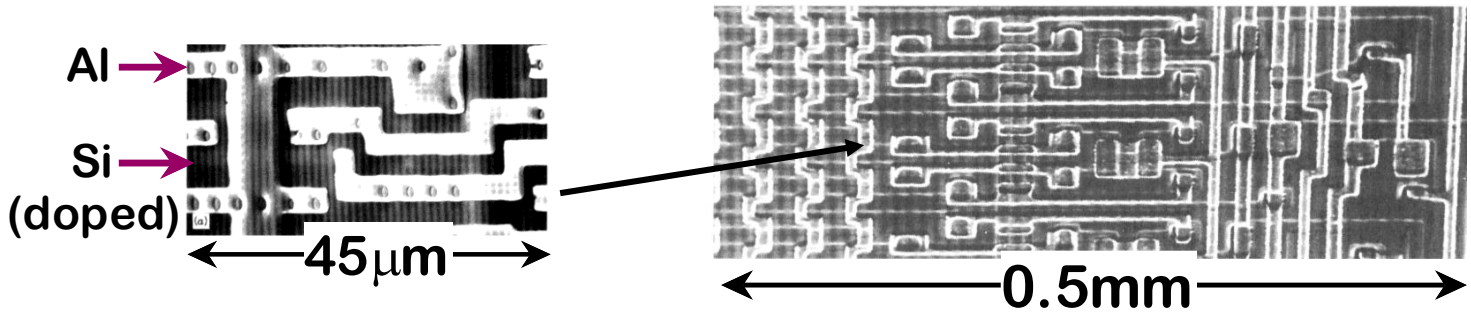
Basic components of integrated circuits (bipolar). The dark areas are the contact pads.



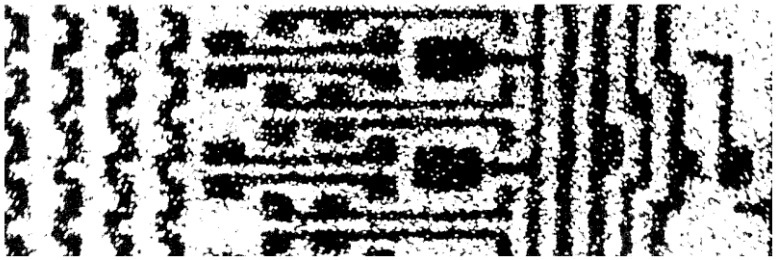
An Intel 16K static random-access 5l67 memory (SRAM) where the squares at the side and lower edges are 100-μm Al thin-film pads contacted by wire bonds.

VIEW OF AN INTEGRATED CIRCUIT

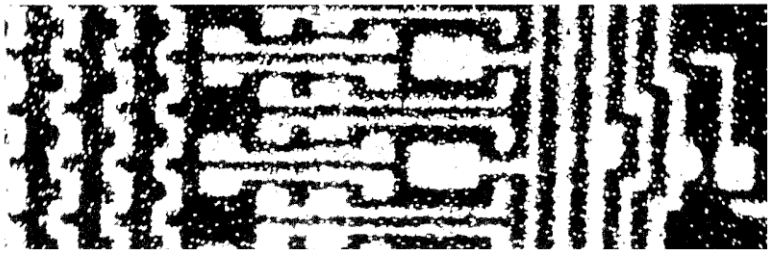
- Scanning electron microscope images of an IC:



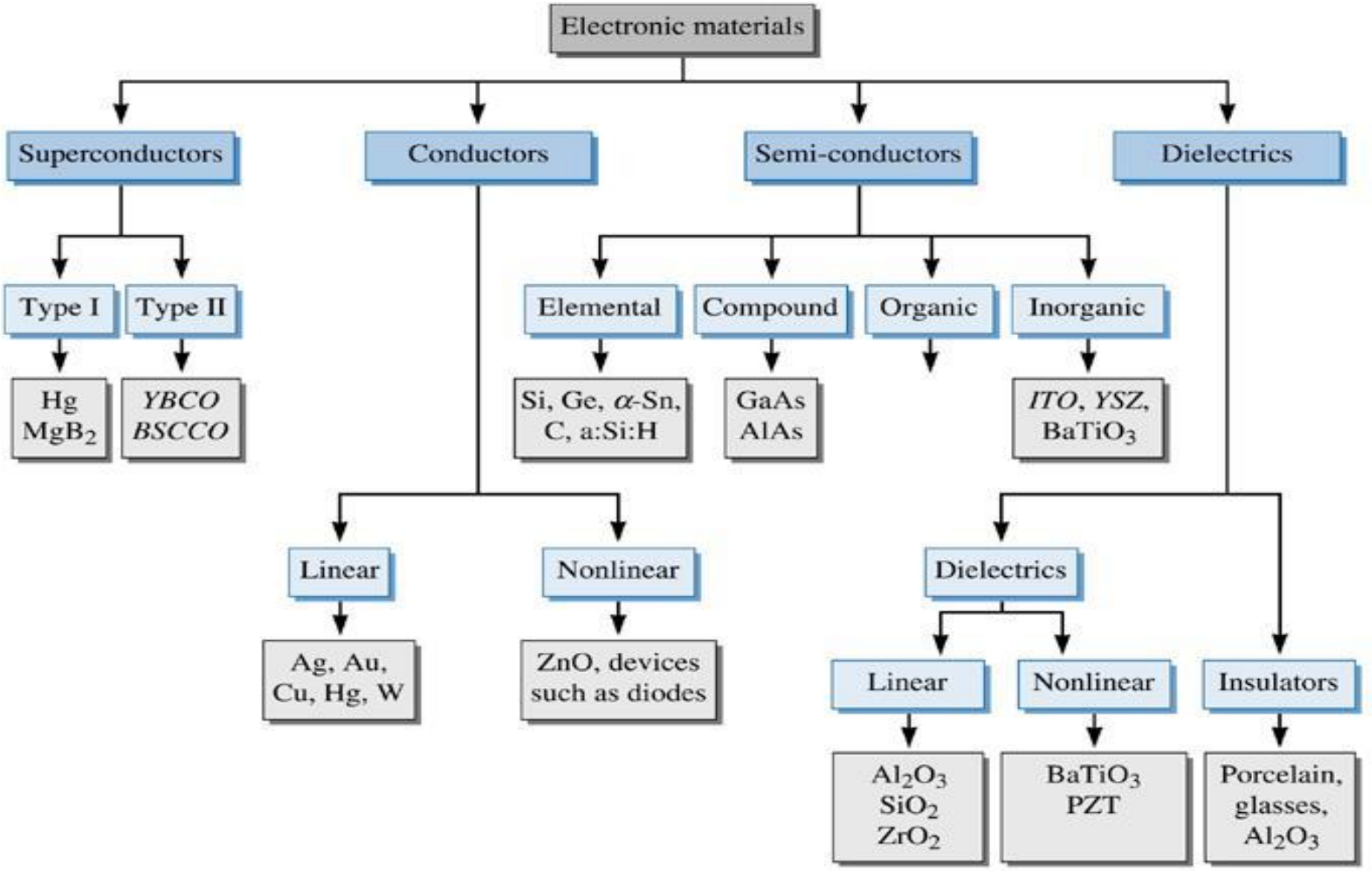
- A dot map showing location of Si (a semiconductor):
  --Si shows up as light regions.



- A dot map showing location of Al (a conductor):
  --Al shows up as light regions.



ELECTRONIC MATERIALS



ELECTRCAL CONDUCTION

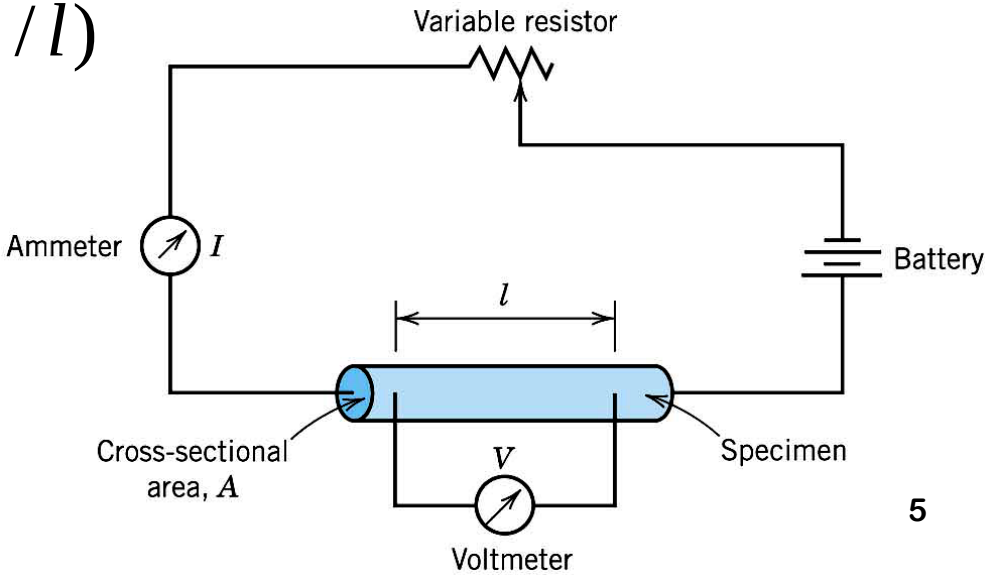
- Ohm's law

$V = IR$ ([V]=[A][Ω])

$R = \rho \dfrac{l}{A}$ (ρ: resistivity [Ωm])

$\sigma = \dfrac{1}{\rho}$ (σ: conductivity [$\Omega^{-1}m^{-1}$])

$J = \sigma E$ $\left(J = I / A,\ E = V / l\right)$

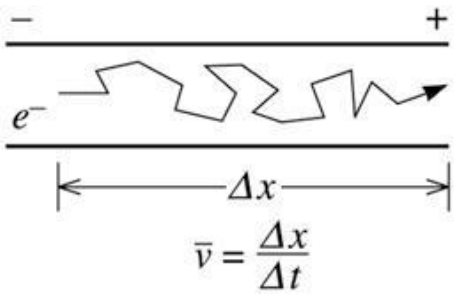


ELECTRCAL CONDUCTIVITY

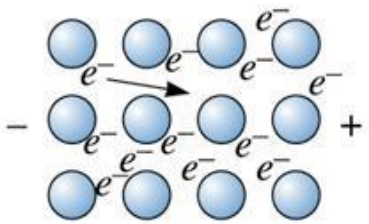
Conducting range	Material	Conductivity, σ ($\Omega^{-1} \cdot m^{-1}$)
Conductors	Aluminum (annealed)	35.36×10^6
	Copper (annealed standard)	58.00×10^6
	Iron (99.99 + %)	10.30×10^6
	Steel (wire)	$5.71–9.35 \times 10^6$
Semiconductors	Germanium (high purity)	2.0
	Silicon (high purity)	0.40×10^{-3}
	Lead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

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

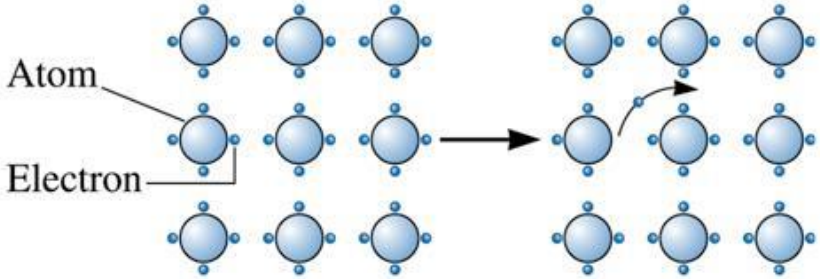
Electron volt = 1 eV = 1.6×10^{-19} Joule = 1.6×10^{-12} erg
1 amp = 1 coulomb/second
1 volt = 1 amp · ohm
$k_B T$ at room temperature (300 K) = 0.0259 eV
c = speed of light 2.998×10^{-8} m/s
ε_0 = perimitivity of free space = 8.85×10^{-12} F/m
q = charge on electron = 1.6×10^{-19} C
Avogadro's number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



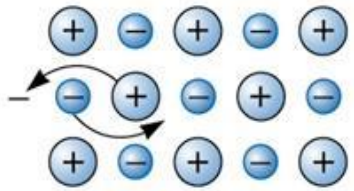
(a)



(b)



(c)



(d)

- charge carrier
  electron (e=1.602x10^{-19} C)
  electron hole
  cation
  anion

BAND STRUCTURE OF SOLIDS

- **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.

- **Holes**

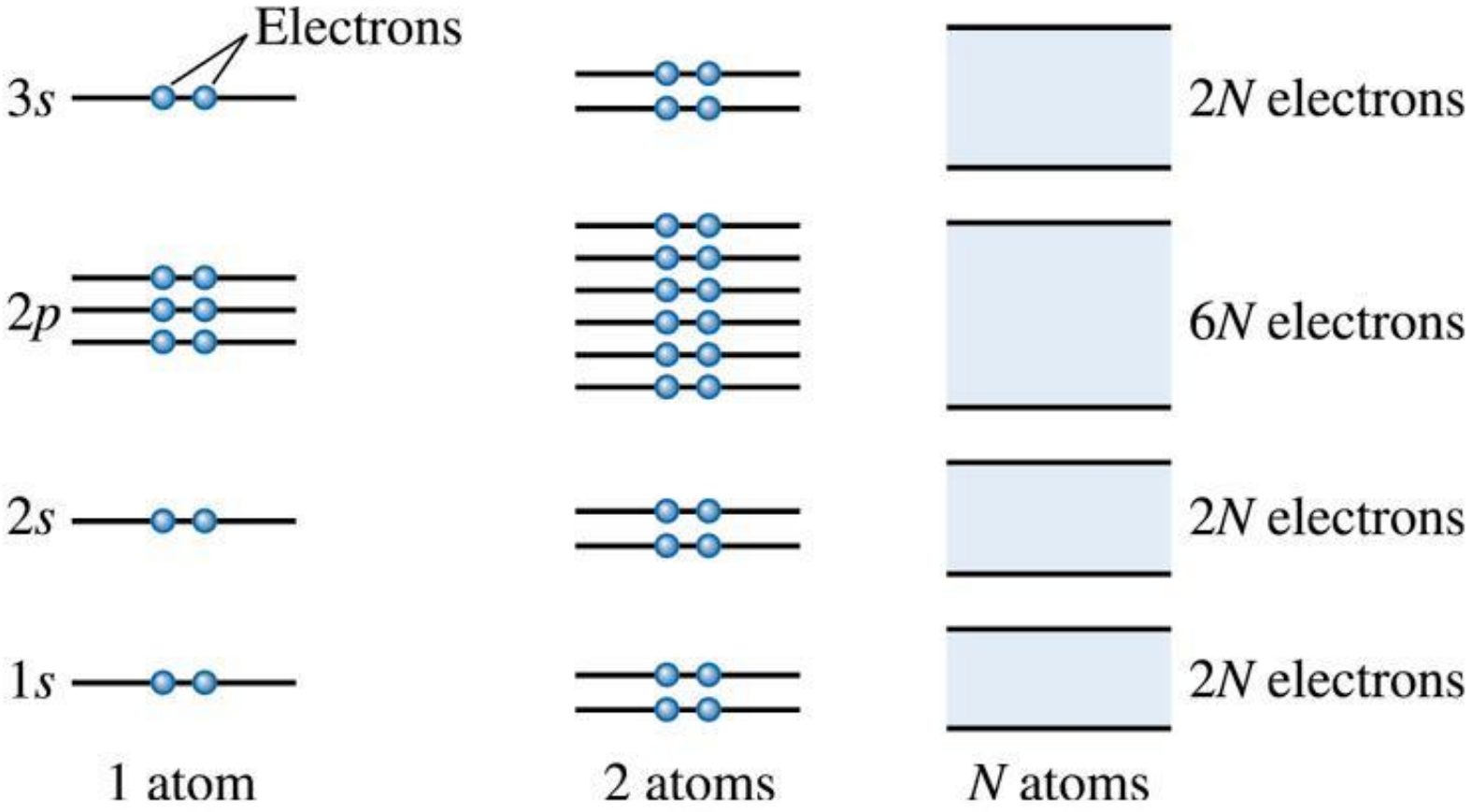
- Unfilled energy levels in the valence band.Because electrons move to fill these holes, the holes move and produce a current.

- **Energy gap (Bandgap)**

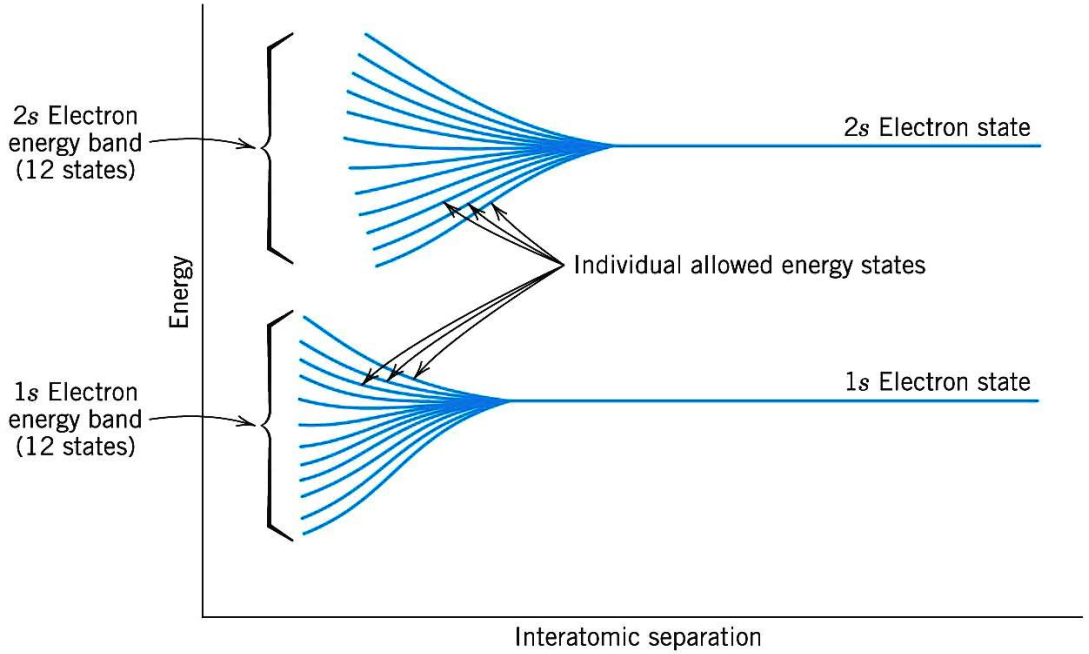
- The energy between the top of the valence band and the bottom of the conduction band that a charge carrier must obtain before it can transfer a charge.

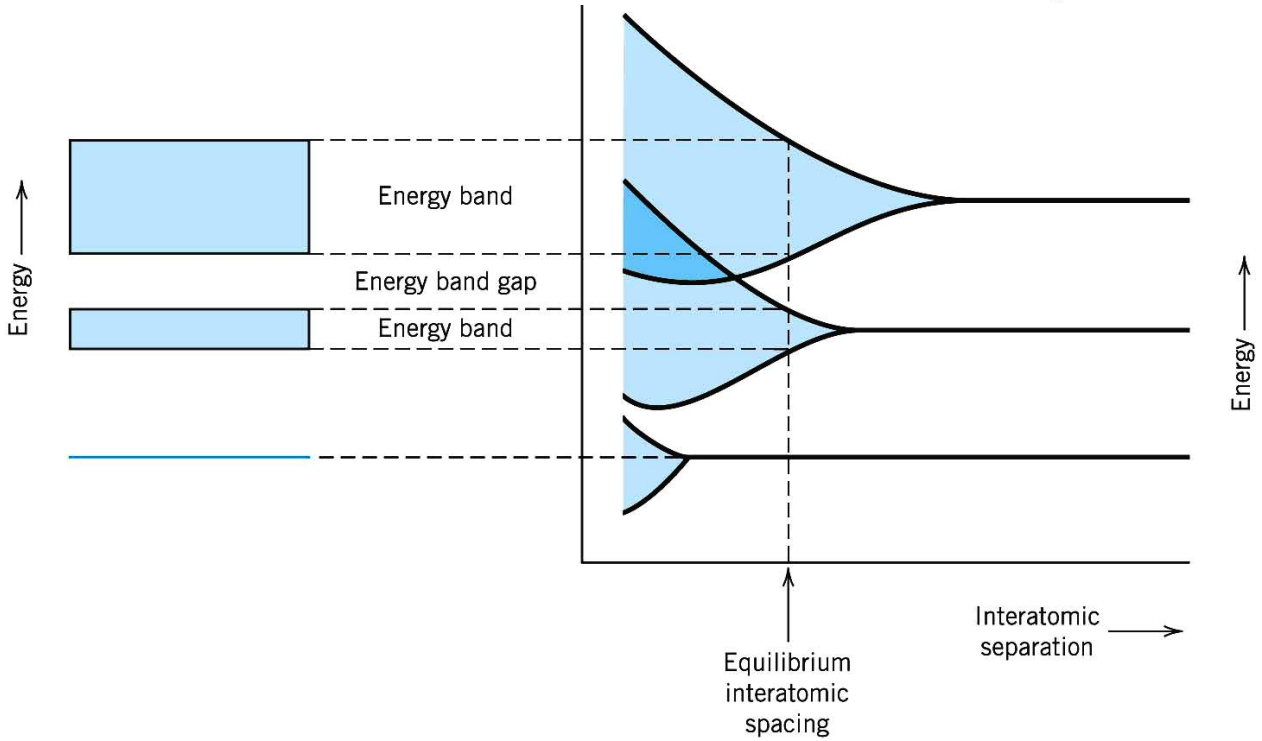
NUMBER OF CHARGE CARRIER

- **energy band**

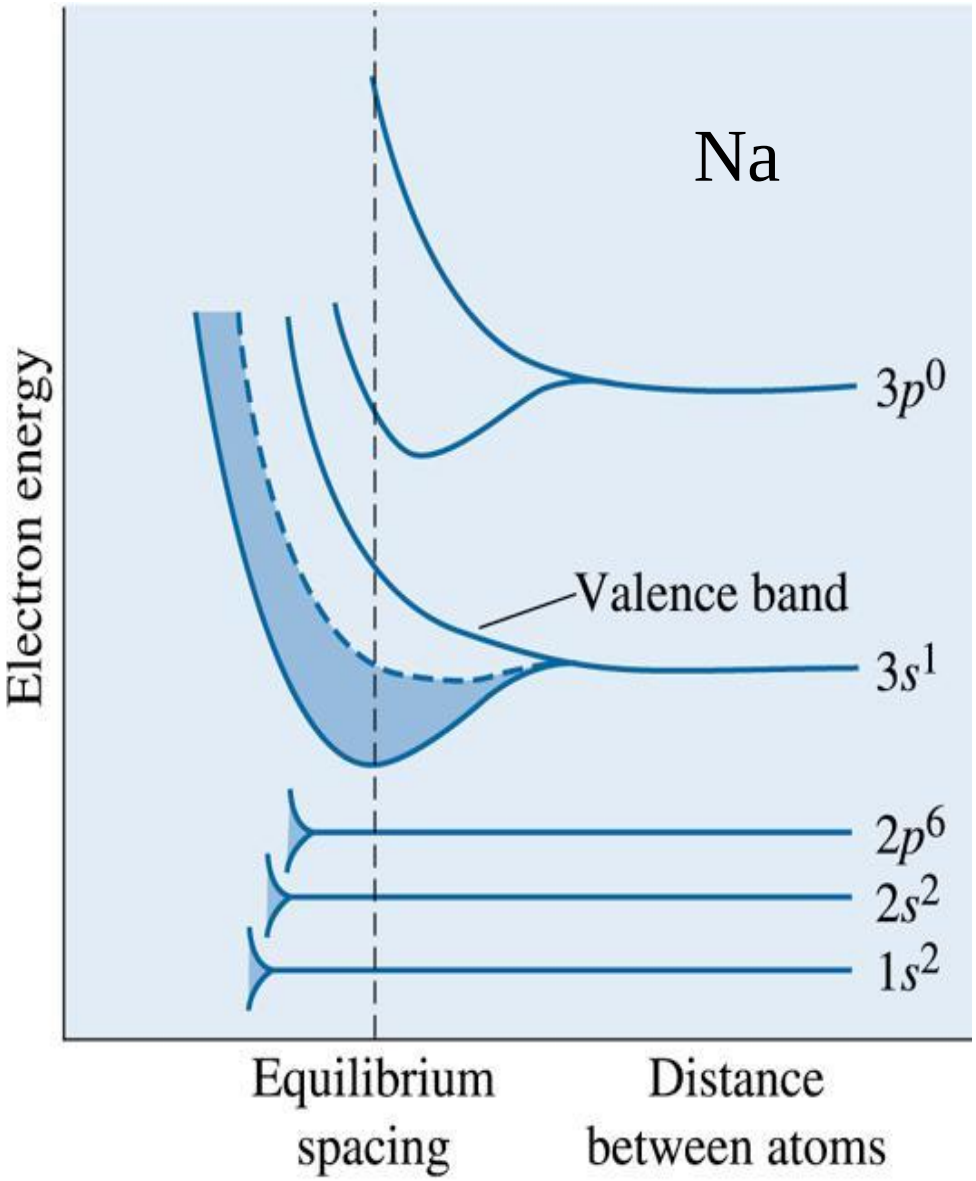


ENERGY BAND

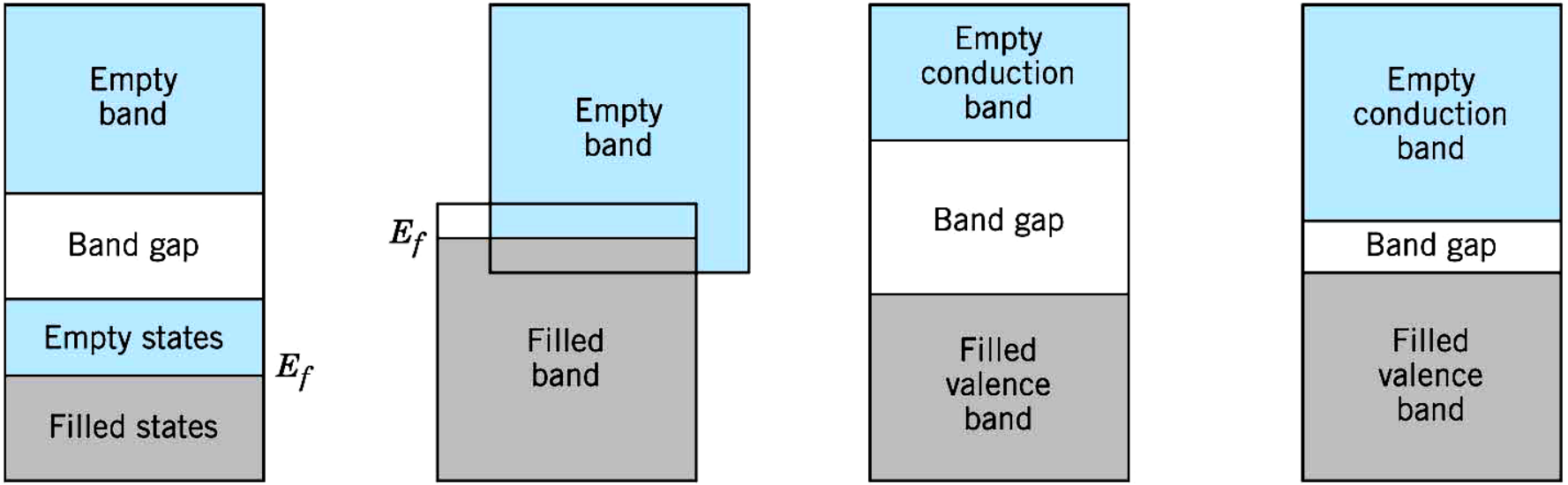

2s Electron energy band (12 states)
2s Electron state
Individual allowed energy states
Energy
1s Electron energy band (12 states)
1s Electron state
Interatomic separation


Energy band
Energy band gap
Energy band
Energy
Energy
Interatomic separation
Equilibrium interatomic spacing

ENERGY BAND


Na
Electron energy
$3p^0$
Valence band
$3s^1$
$2p^6$
$2s^2$
$1s^2$
Equilibrium spacing
Distance between atoms

ELECTRON BAND STRUCTURE



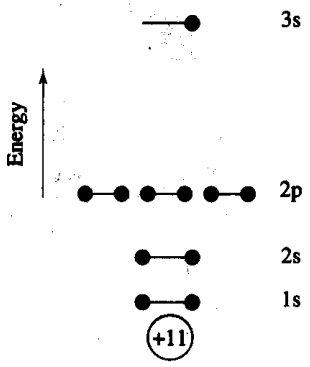
metal
Ex) Cu ($3d^{10}4s^1$)

Mg($3s^2$)

insulator
> 2eV

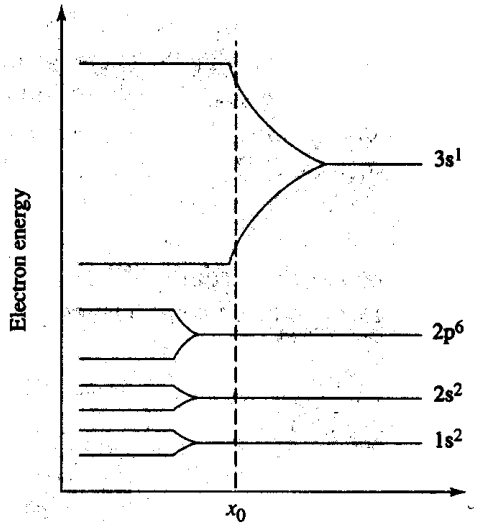
semiconductor
< 2eV

ENERGY BAND FOR CONDUCTOR



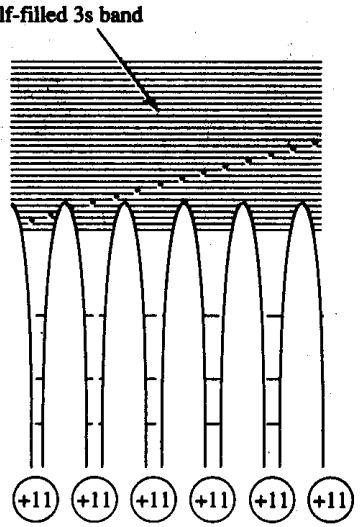
Single Na atom

(a)



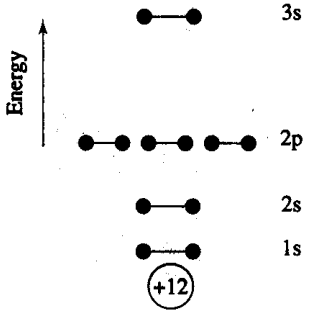
Distance between atoms

(b)



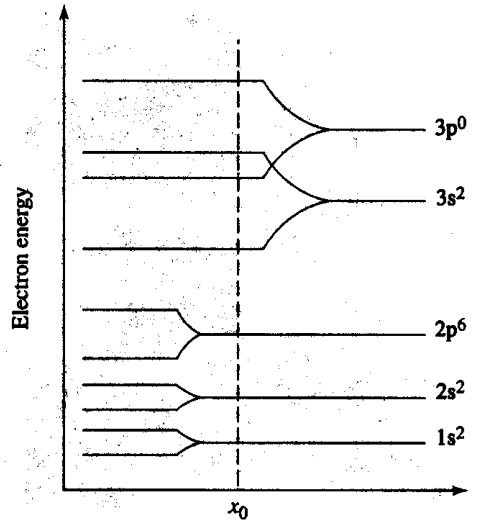
Many adjacent Na atoms

(c)



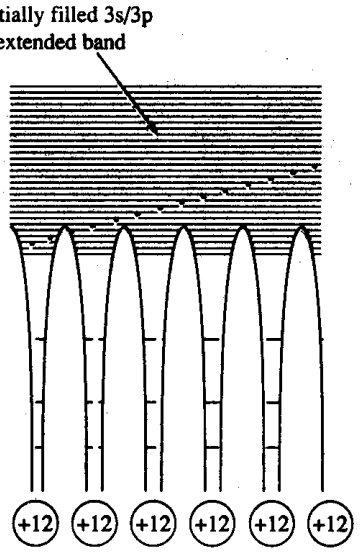
Single Mg atom

(d)



Distance between atoms

(e)

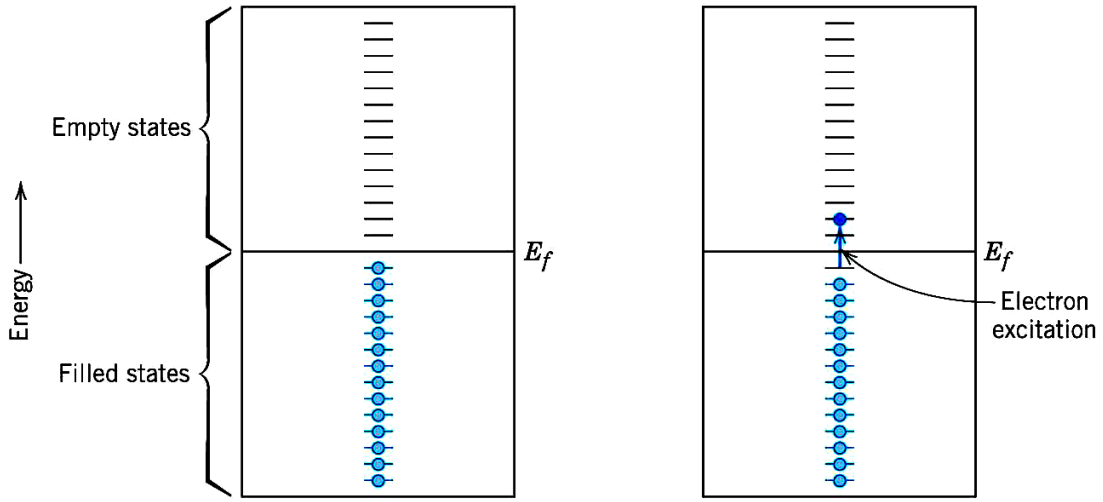


Many adjacent Mg atoms

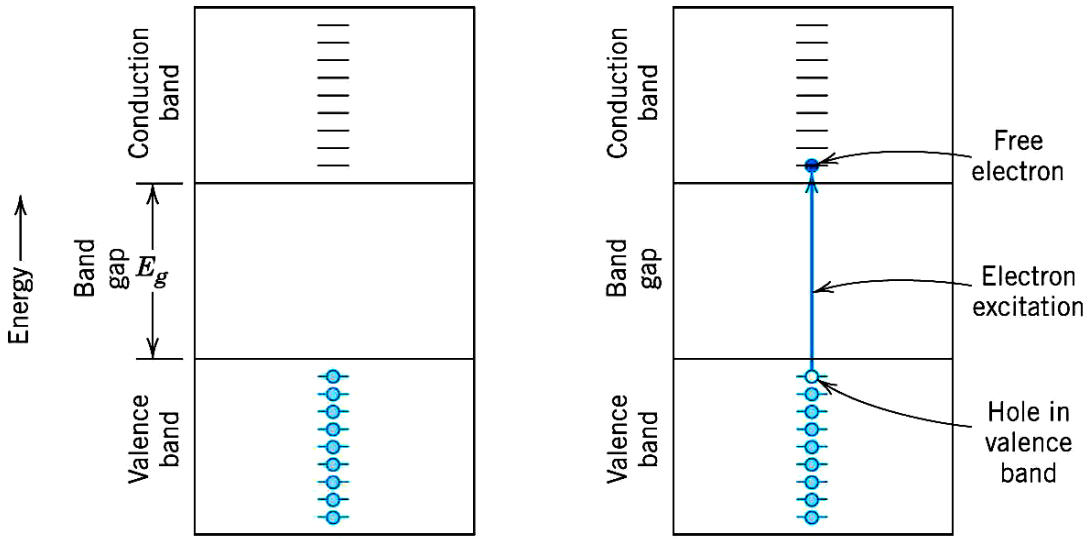
(f)

CONDUCTION IN TERMS OF BAND AND ATOMIC BONDING MODELS

- **metals**



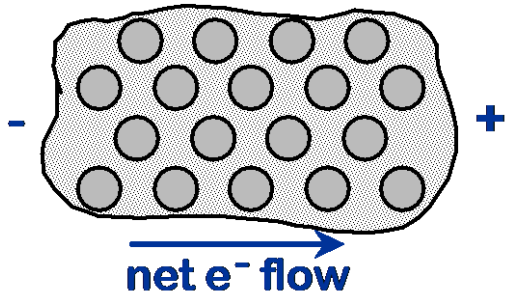
- **insulators and semiconductors**



CONDUCTION & ELECTRON TRANSPORT

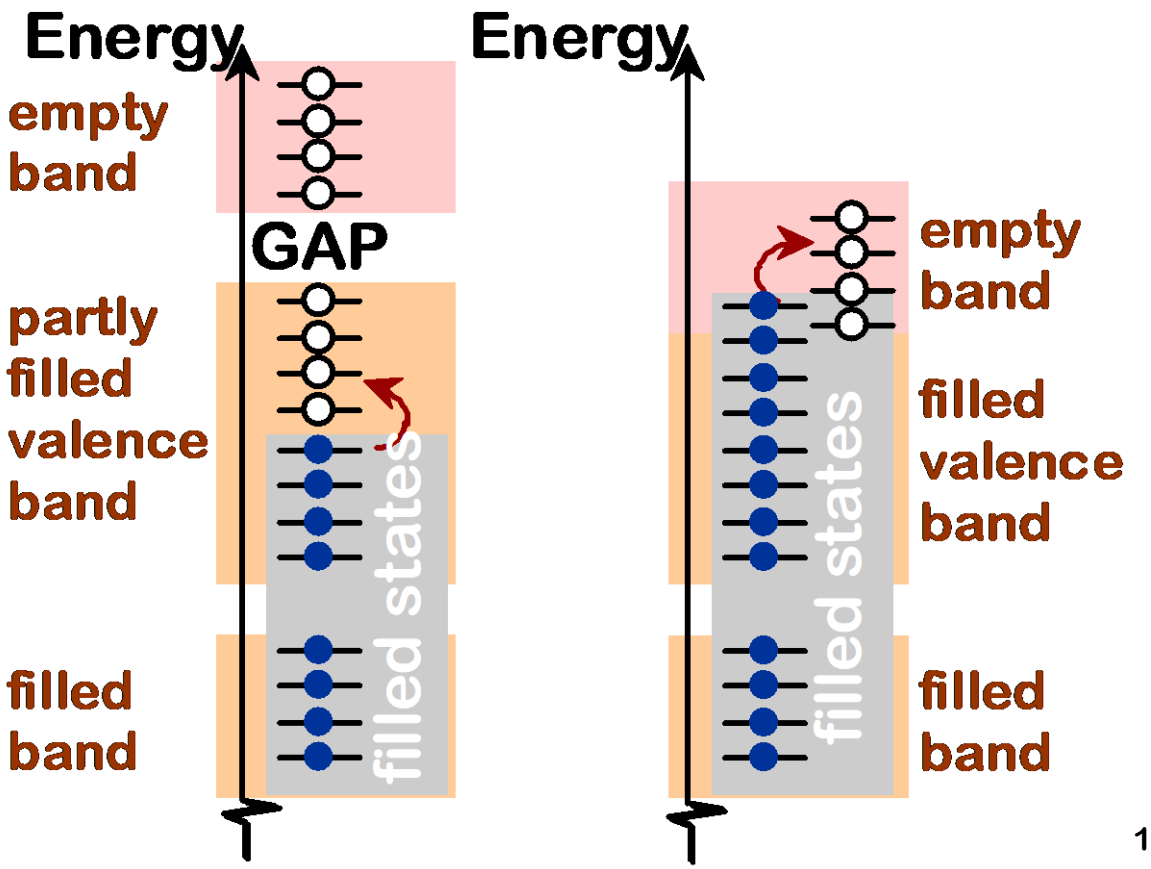
- **Metals:**

-- Thermal energy puts many electrons into a higher energy state.



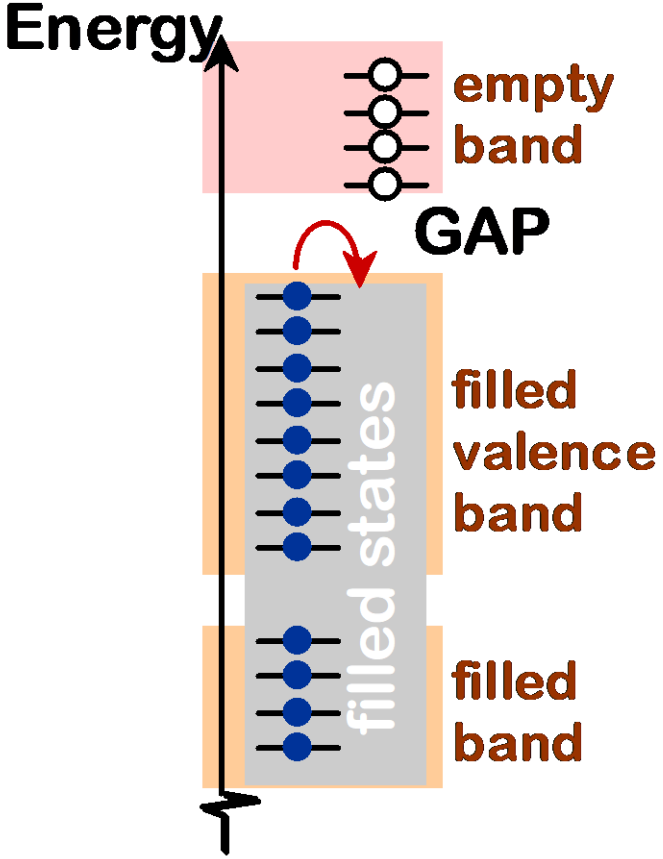
- **Energy States:**

-- the cases below for metals show that nearby energy states are accessible by thermal fluctuations.

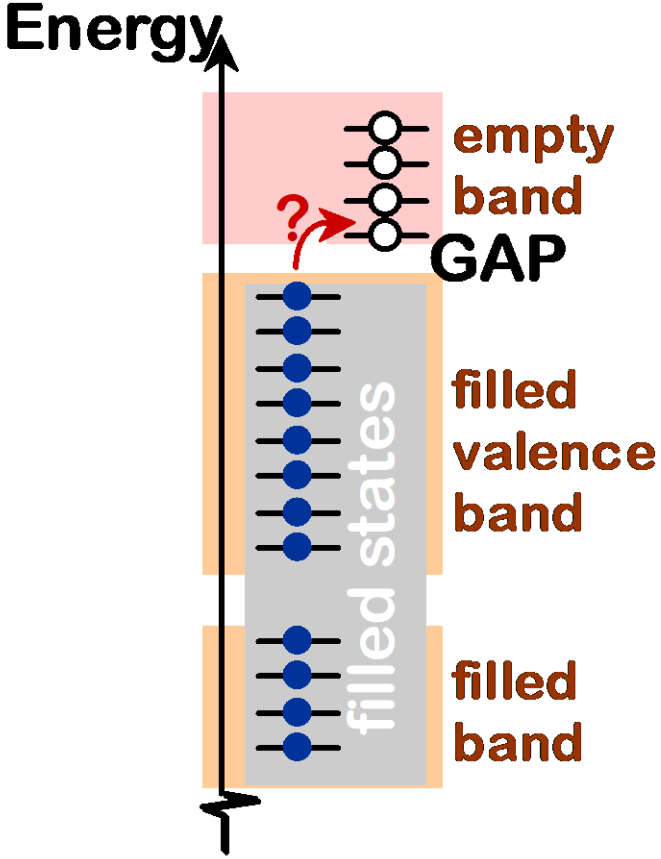


ENERGY STATES: INSULATORS AND SEMICONDUCTORS

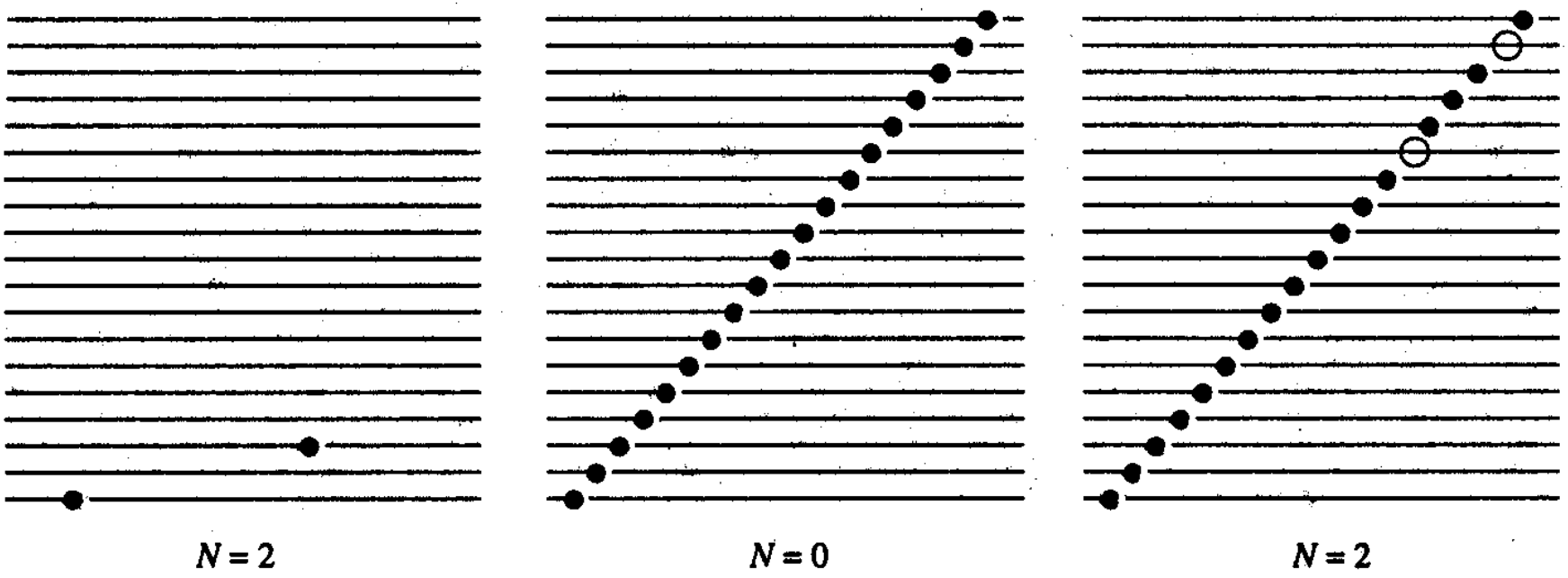
- **Insulators:**
  --Higher energy states not accessible due to gap.



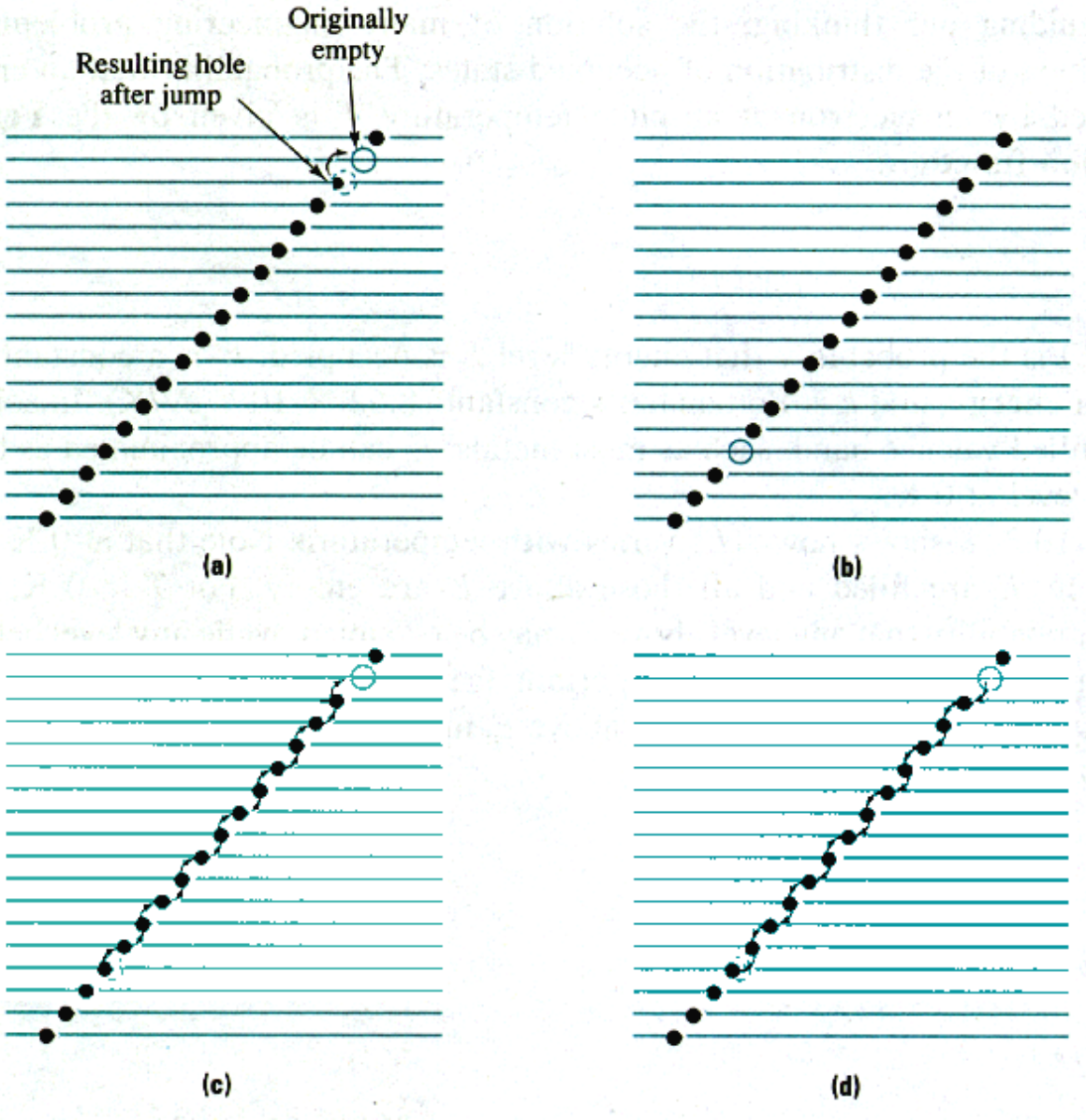
- **Semiconductors:**
  --Higher energy states separated by a smaller gap.



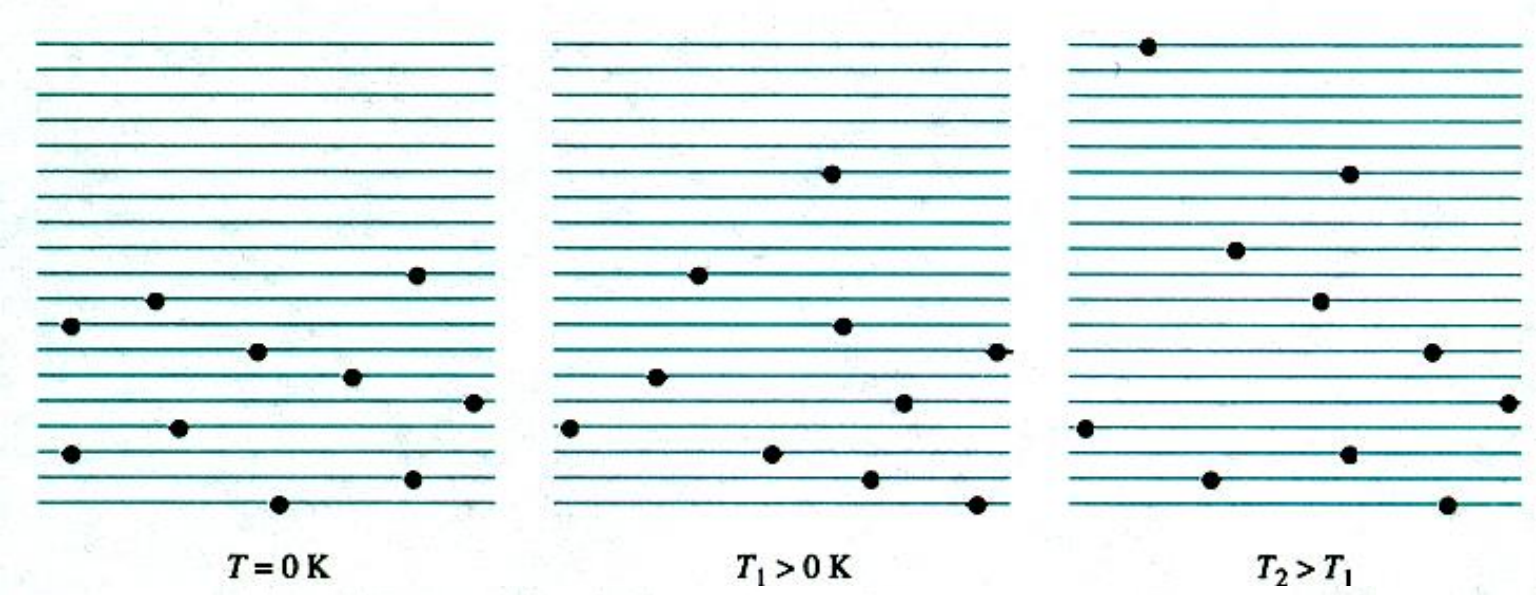
ELECTRON DISTRIBUTION WITHIN AN ENERGY BAND

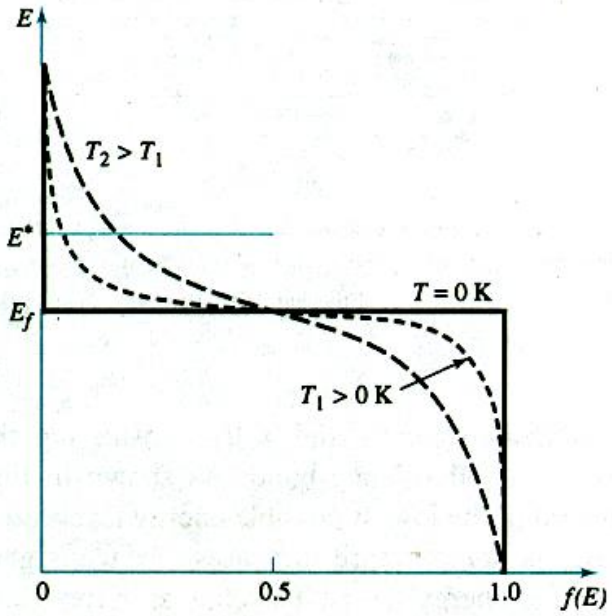


ELECTRON DISTRIBUTION WITHIN AN ENERGY BAND

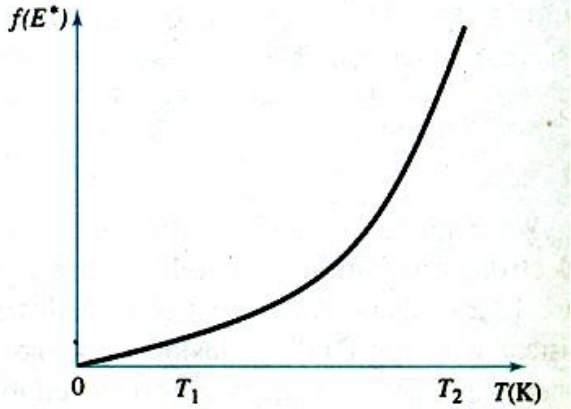


FERMI-DIRAC DISTRIBUTION

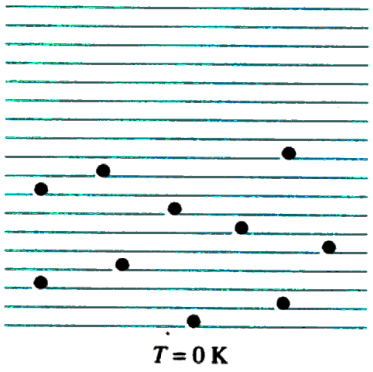


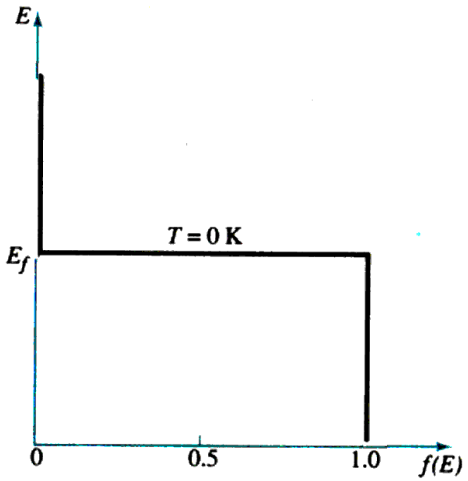


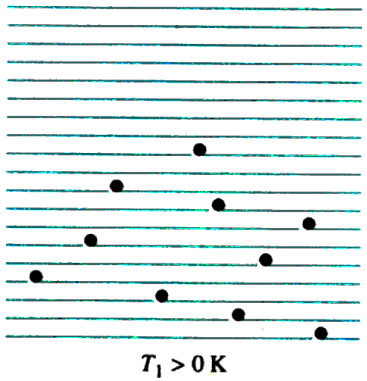
$$f(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$

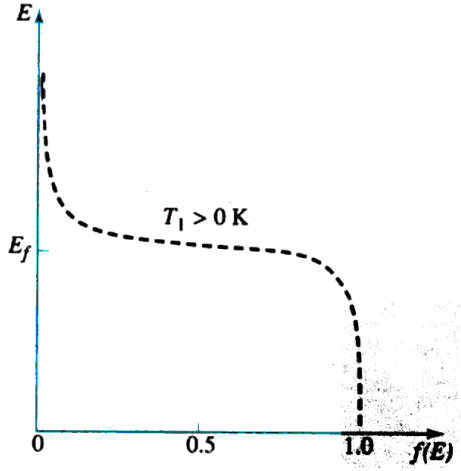


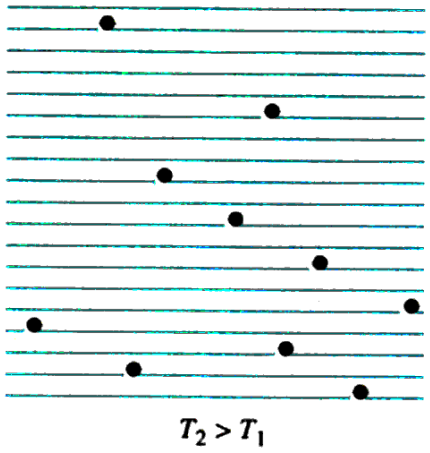
FERMI-DIRAC DISTRIBUTION

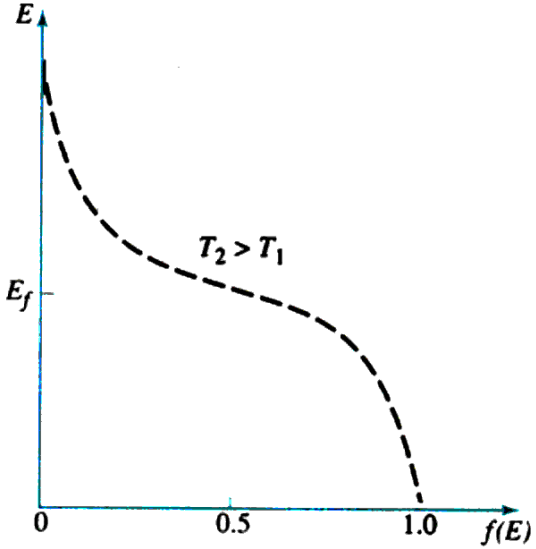




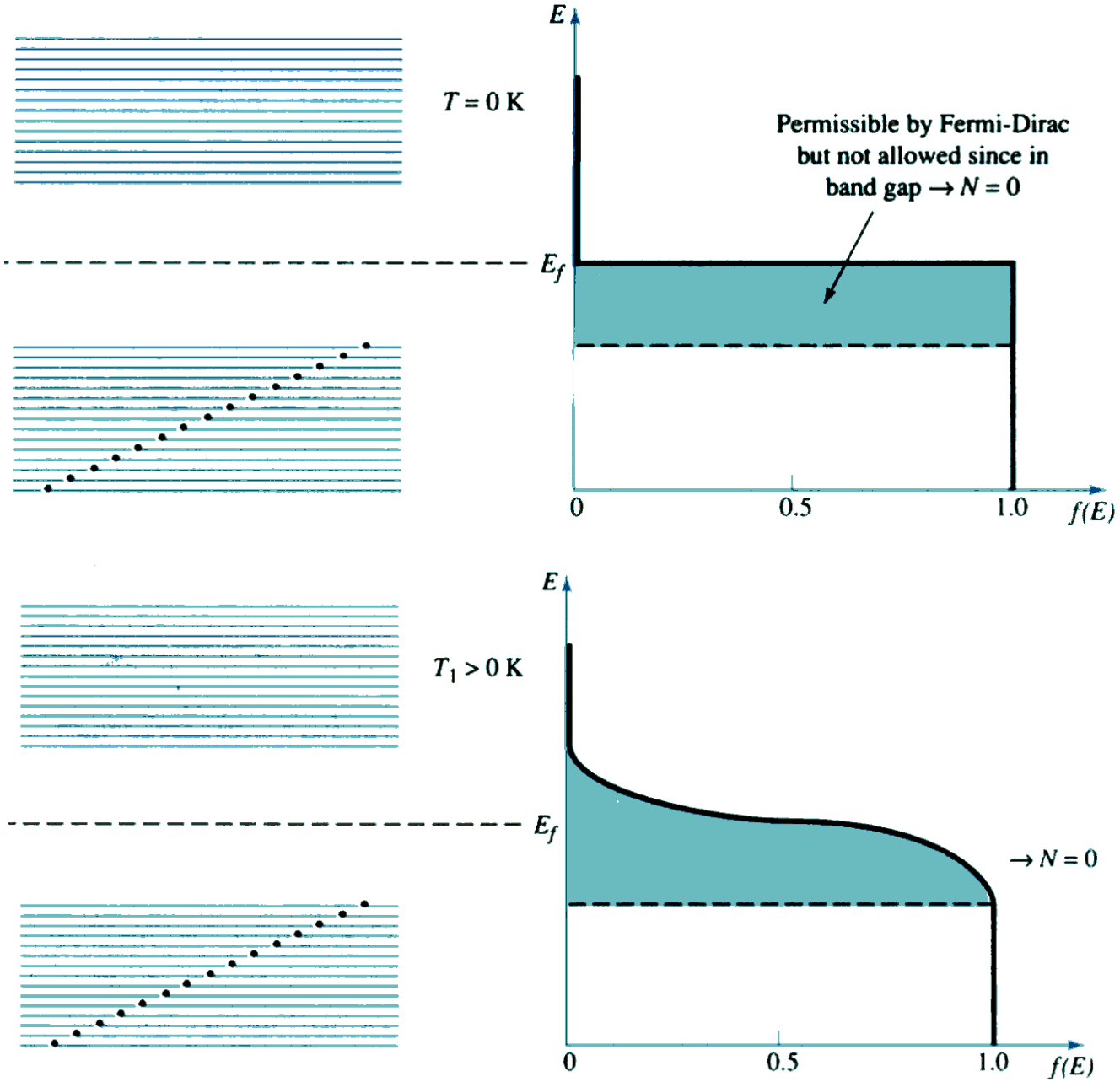




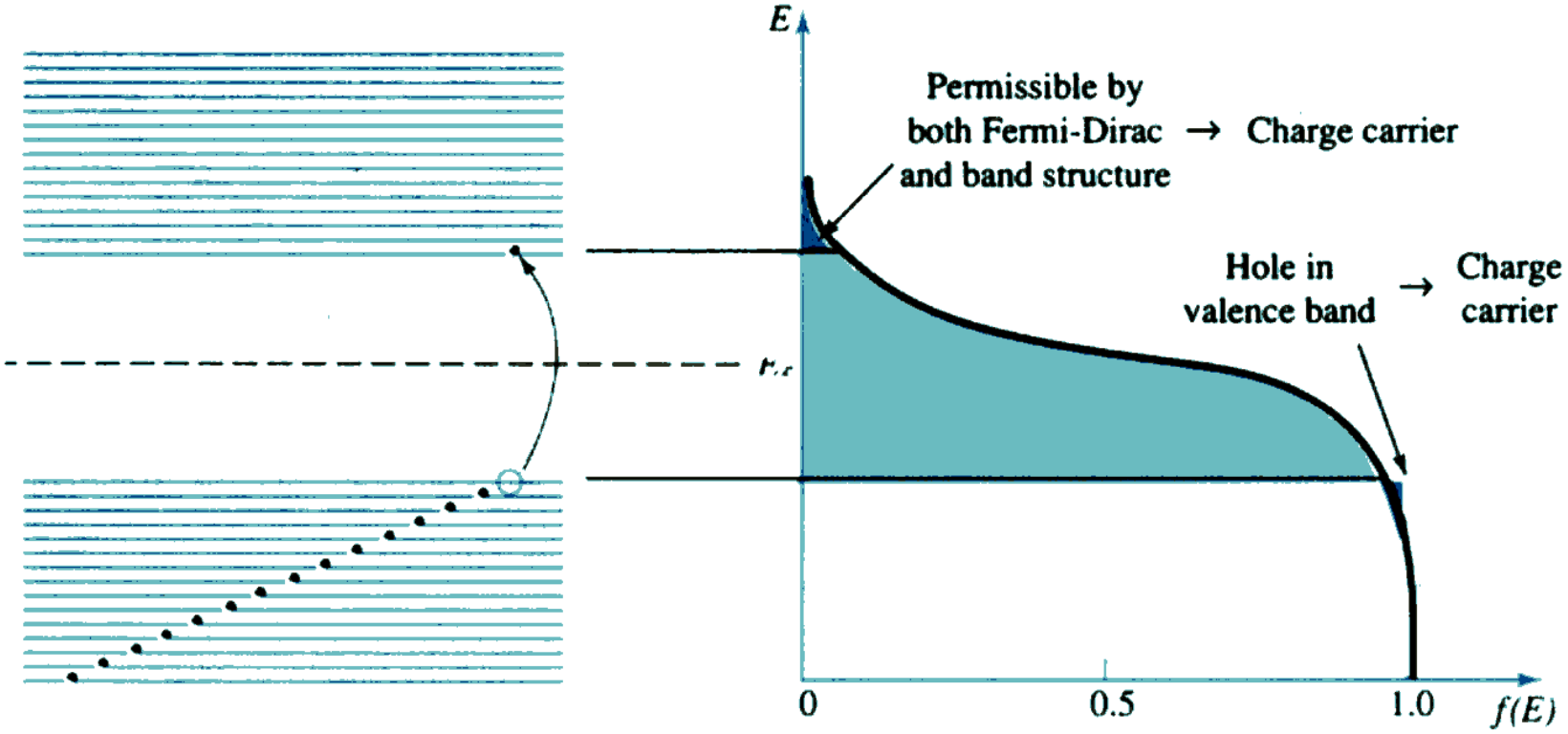




FERMI-DIRAC DISTRIBUTION



FERMI-DIRAC DISTRIBUTION



$$N_e = \int_{E_C}^{\infty} f(E)g(E)dE \qquad g(E): \textit{ density of state}$$

$$= N_o \exp\left(\frac{-E_g}{2kT}\right)$$

DENSITY OF STATE

- g(E)dE= number of electron states per unit volume in the energy range (E, E+dE)

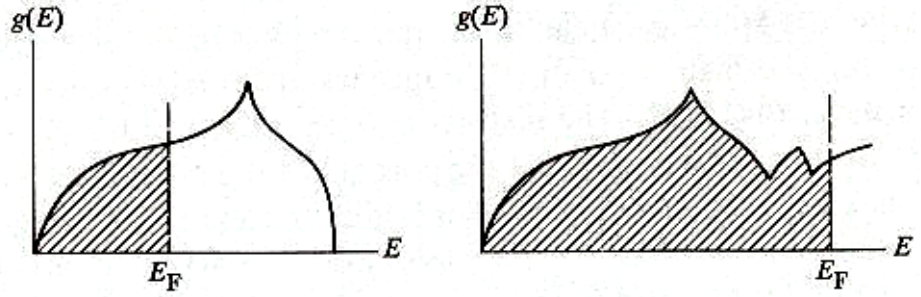
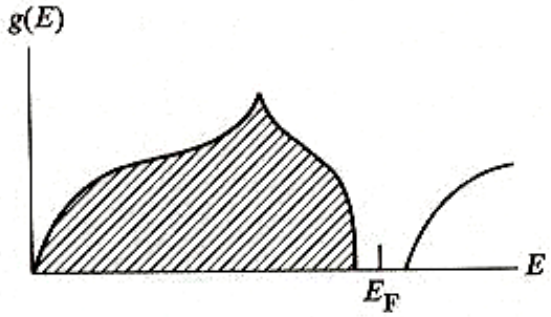


Fig. 5.27 The position of the Fermi energy in (a) a monovalent metal, and (b) a divalent metal.



The position of the Fermi energy in an insulator.

at T=0 K

$$\int_0^{E_F} g(E)dE = n$$

EXAMPLE

Ex1) This example deals with the Fermi-Dirac distribution function.

a. Show that $f(E_f)=0.5$ at any temperature.

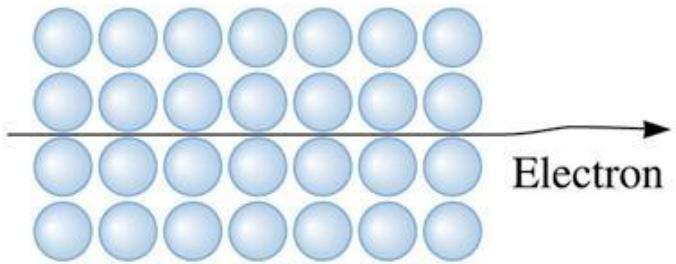
b. Show that at 0K, $f(E>E_f)=0$ and $f(E<E_f)=1.0$.

c. Calculate the values of $f(E_f+0.5\ eV)$ at 0, 300, and 600K.

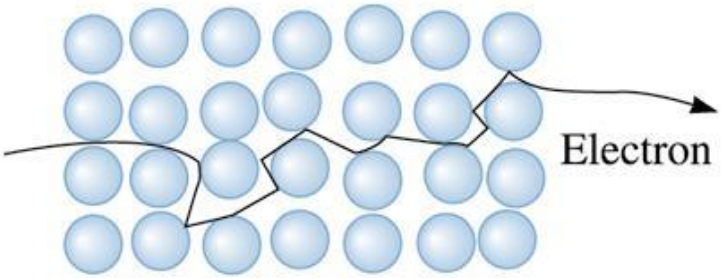
d. Repeat part c for f(Ef+2.0 eV).

Ex2) What is the probability of an electron being thermally promoted to the conduction band in diamond (E_g=5.6eV) and silicon (E_g=1.07eV) at room temperature.

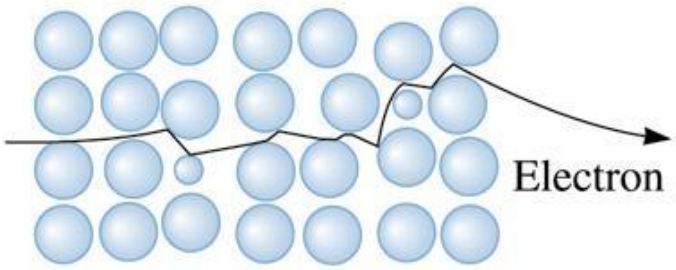
ELECTRON MOBILITY



(a)



(b)



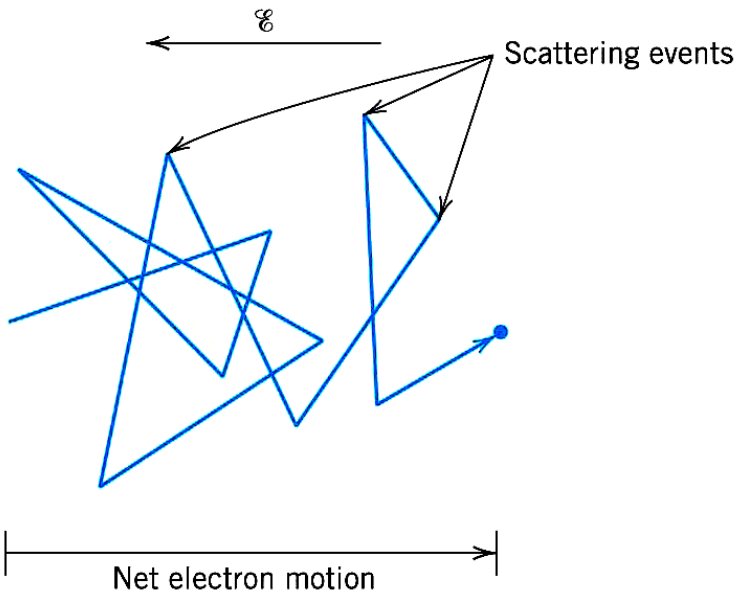
(c)

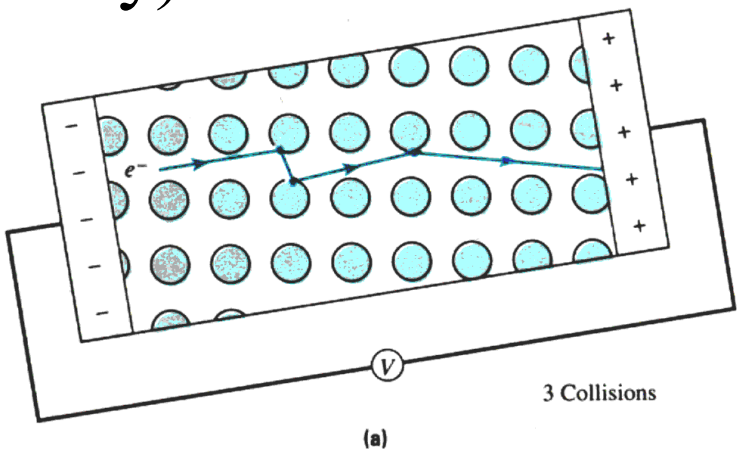
ELECTRON MOBILITY

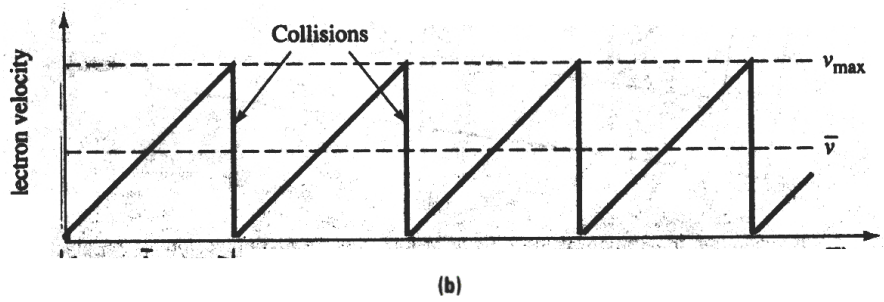
- **electron motion under electric field**

$\bar{\upsilon}_d = a\bar{t}$ ($\bar{\upsilon}_d$: drift velocity, $\bar{t}$: mean time)

$\bar{\upsilon}_d = \mu_e E$ (μ_e : electron mobility)







- **random velocity: v_r**
  drift velocity: v_d $v_r/v_d \sim 10^8$

ELECTRON MOBILITY

- **conductivity**

$\sigma = n|e|\mu$ n: number of mobile charge carrier per unit volume [m^{-3}]

$|e|$: charge per carrier [C]

μ: mobility of charge carrier [m^2/Vs]

- **For metals**

$\sigma = 5\times10^{7}\ \Omega^{-1}m^{-1}$ $n = 10^{29}\ m^{-3}$ $e = 1.6\times10^{-19}\ C$

$\mu = 3.1\times10^{-3}\ m^2/Vs$

Electrical Conductivities and Other Transport Parameters for Metals

Element	σ, $\text{ohm}^{-1}\,\text{m}^{-1}$	N, m^{-3}	τ, s	v_F, m/s	l, Å	E_F, eV	E_F(obs.), eV	m^*/m_0
Li	1.07×10^{7}	4.6×10^{28}	0.9×10^{-14}	1.3×10^{6}	110	4.7	3.7	1.2
Na	2.11	2.5	3.1	1.1	350	3.1	2.5	1.2
K	1.39	1.3	4.3	0.85	370	2.1	1.9	1.1
Rb	0.80	1.1	2.75	0.80	220	1.8	—	—
Cs	0.50	0.85	—	0.75	160	1.5	—	—
Cu	5.88	8.45	2.7	1.6	420	7.0	7.0	1.0
Ag	6.21	5.85	4.1	1.4	570	5.5	—	—
Au	4.55	5.90	2.9	1.4	410	5.5	—	—
Zn	1.69	13.10	—	1.82	—	9.4	11.0	0.85
Cd	1.38	9.28	—	1.62	—	7.5	—	—
Hg	0.10	—	—	—	—	—	—	—
Al	3.65	18.06	—	2.02	—	11.6	11.8	—
Ga	0.67	15.30	—	1.91	—	10.3	—	—
In	1.14	11.5	—	1.74	—	8.6	—	—

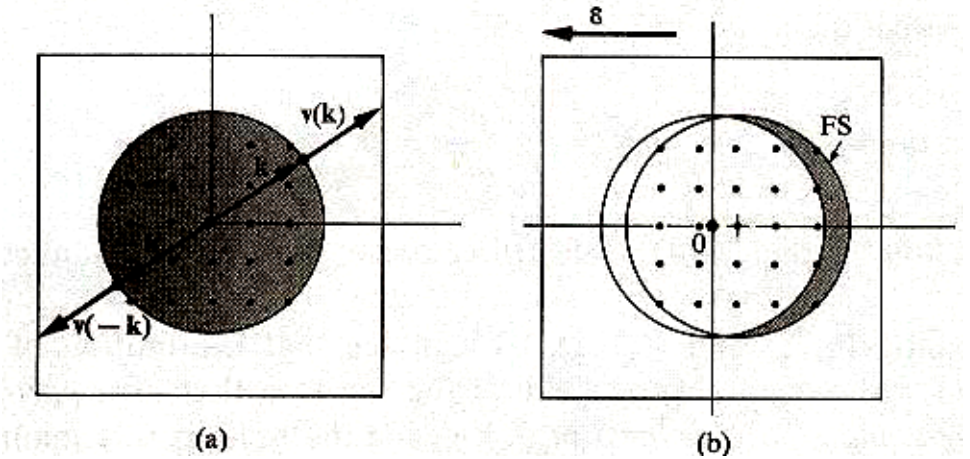
Values quoted are for metals at room temperature. The concentration is found by using the usual chemical valences. The Fermi velocity v_F and E_F are evaluated by using $m^* = m_0$ and the appropriate equation from Section 4.6. The Fermi energy E_F (observed) is the experimentally determined value as discussed in Chapter 6. The effective mass m^* is determined by using the experimental value E_F (observed) and the relation $E_F = (\hbar/2m^*)(3\pi^2N)^{2/3}$, Eq. (4.34).

ELECTRICAL CONDUCTIVITY

- **free electron model**

  - current is carried equally by all electrons, each moving with a very small velocity v_d
  - current is carried by very few electrons only, all moving at high velocity

$$\sigma = \frac{Ne^2\tau}{m^*}$$

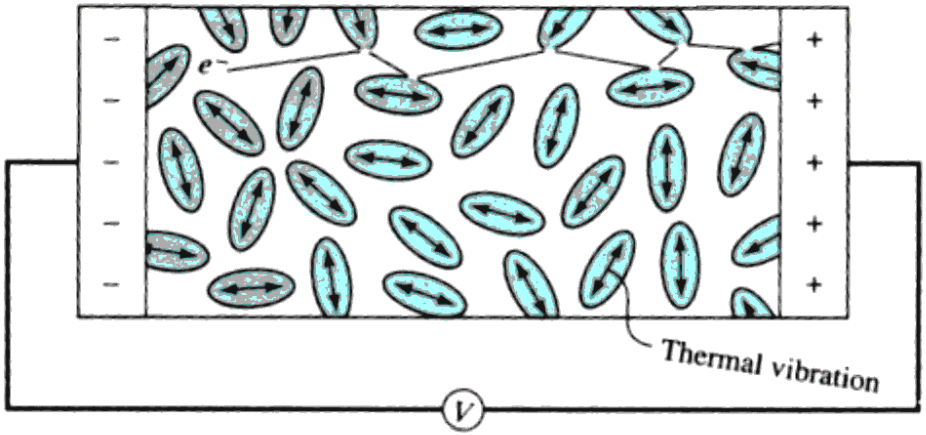


- **band theory**

  - depends on the Fermi velocity and the collision time, but also on the density of states at the Fermi surface

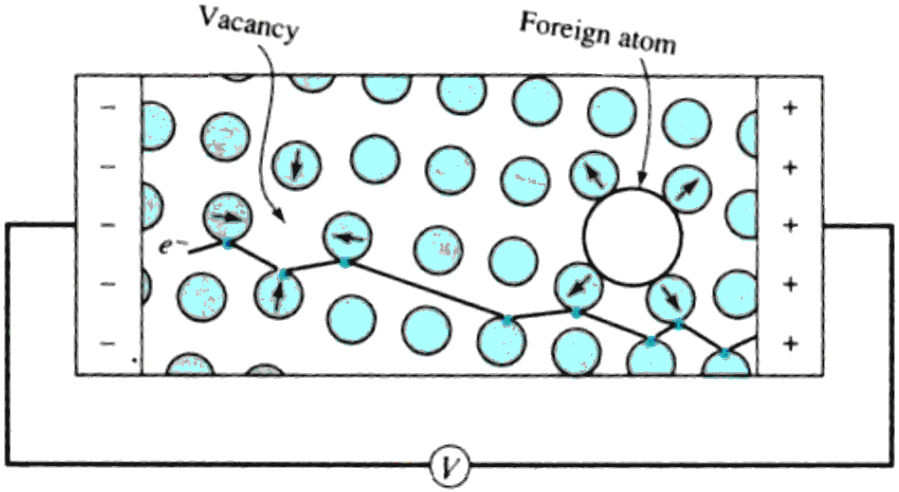
$$\sigma = \frac{1}{3} e^2 v_F^2 \tau_F g(E_F)$$

ELECTRON MOBILITY



(a) 6 Collisions

$$\frac{\partial \mu}{\partial T} < 0$$



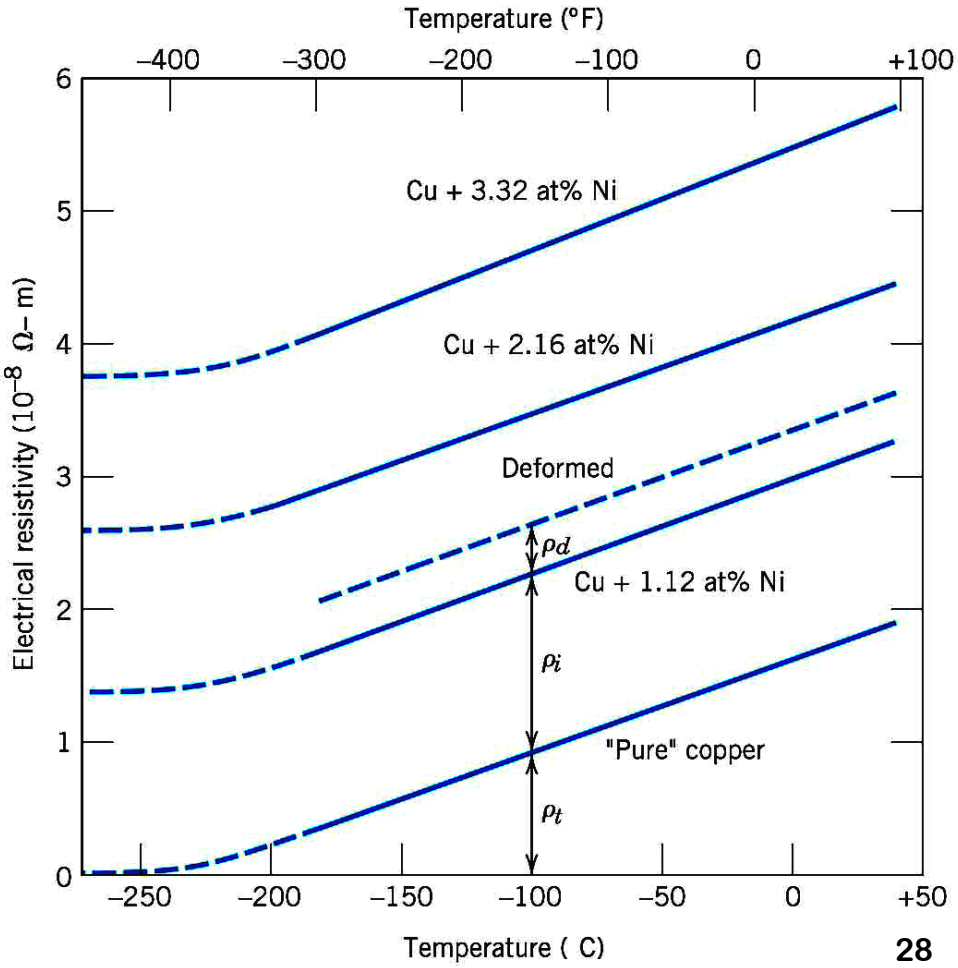
(b) 8 Collisions

$$\frac{\partial \mu}{\partial N_d} < 0$$

ELECTRICAL RESISTIVITY OF METALS

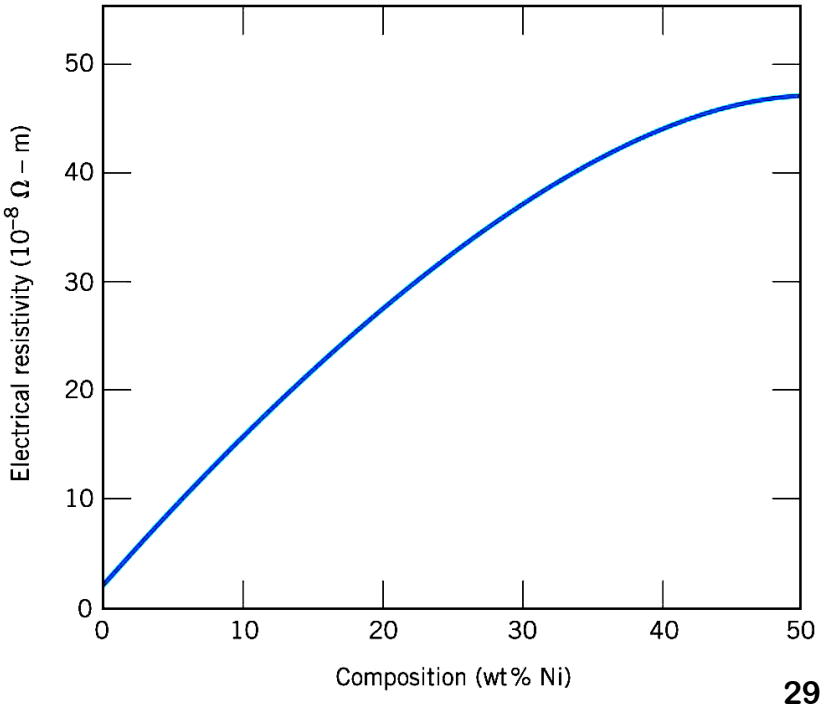
- $\sigma = N_e q_e \mu_e$
- $N_e q_e$: independent of temp. and microstructure
- scattering $\rightarrow$ μ_e
- $\rho_{total} = \rho_t + \rho_i + \rho_d$

(Matthiessen's rule)

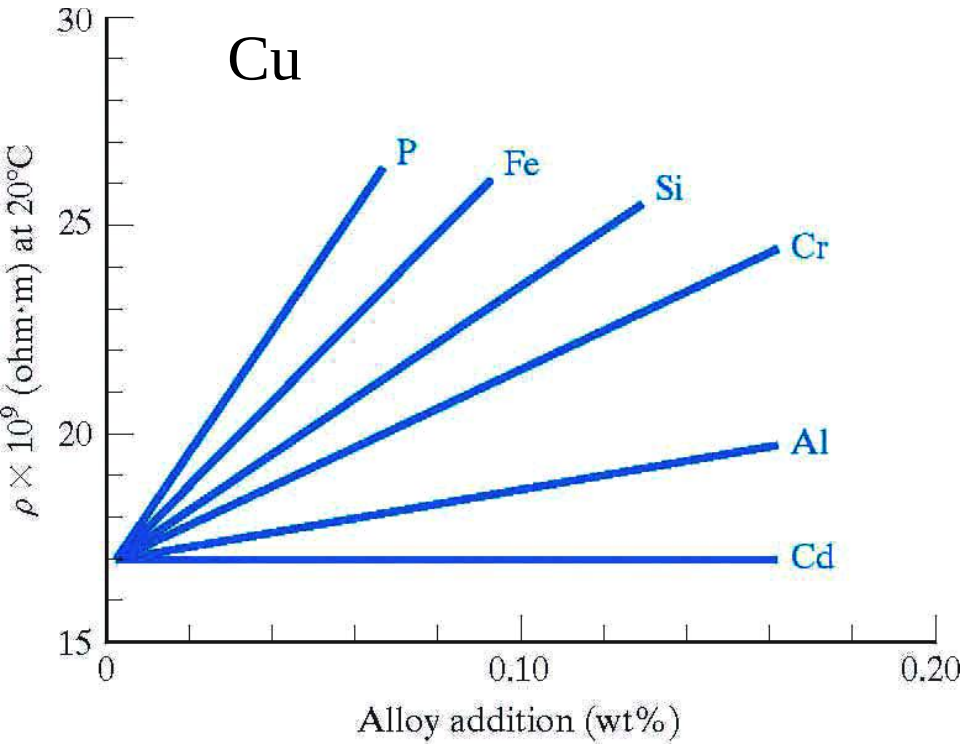


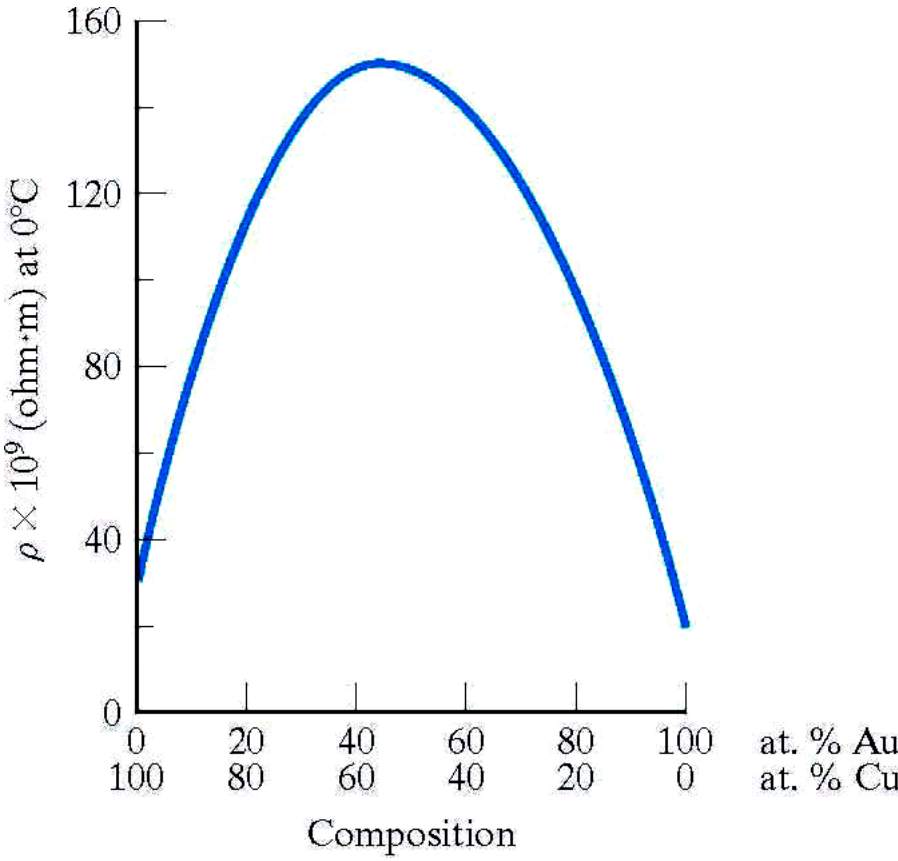
ELECTRICAL RESISTIVITY OF METALS

- **temperature**
  - $\partial\mu/\partial T<0 \rightarrow \partial\sigma/\partial T<0$
  - $\rho_t = \rho_o + \alpha T$
- **impurities**
  - $\rho_i = Ac_i(1-c_i)$
  - $\rho_i = \rho_\alpha V_\alpha + \rho_\beta V_\beta$

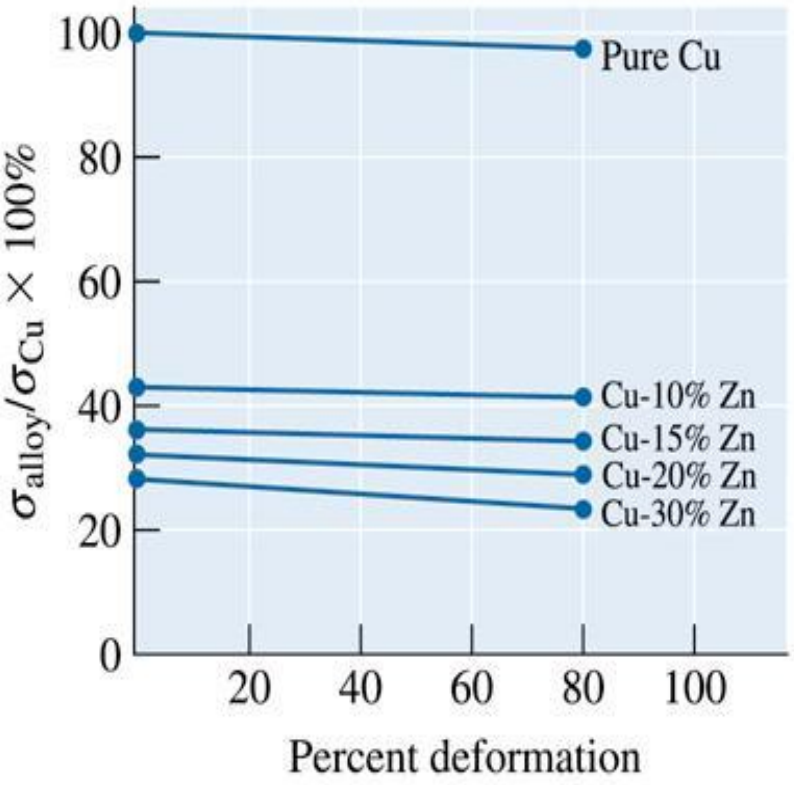


ELECTRICAL RESISTIVITY OF METALS

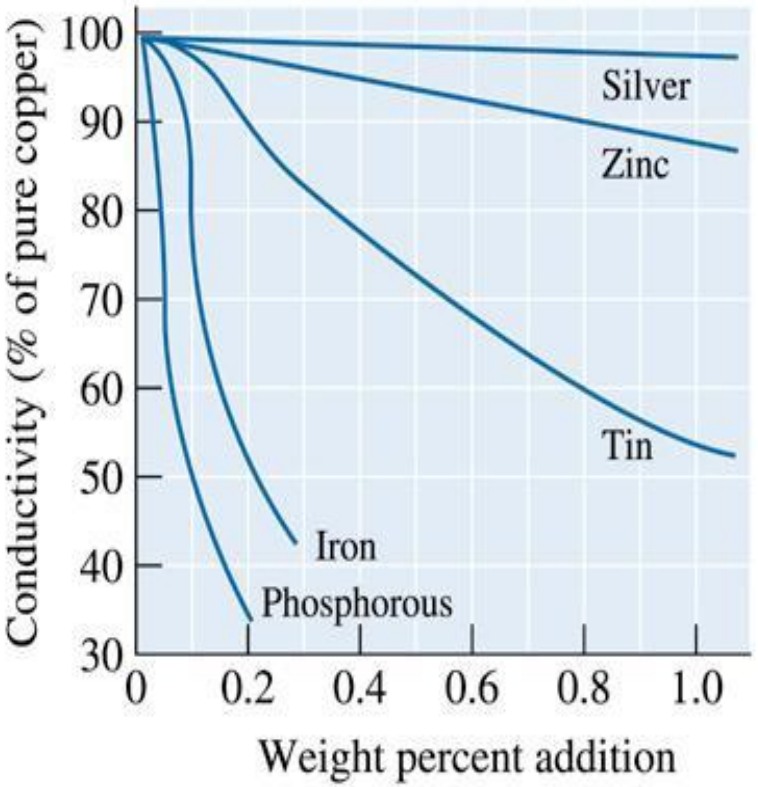




ELECTRICAL RESISTIVITY OF METALS



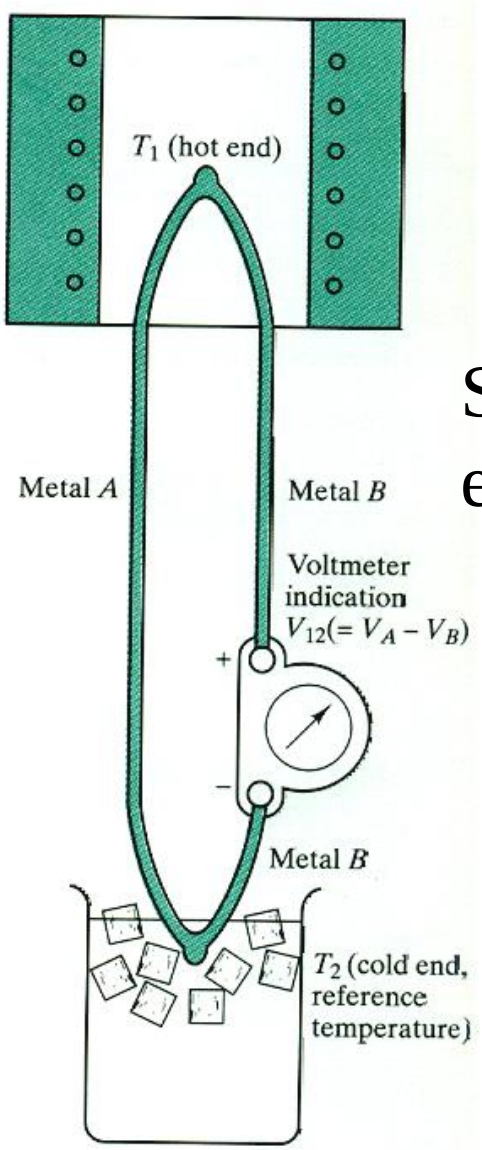
(a)



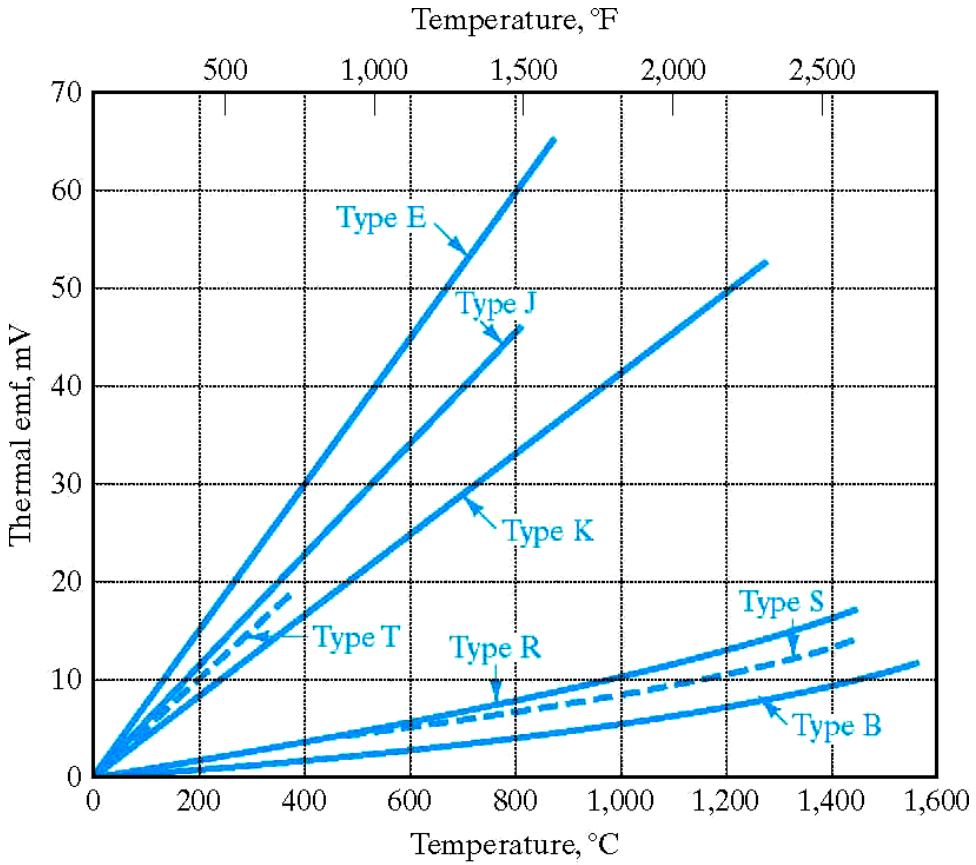
(b)

APPLICATIONS

- **thermocouple**



Seebeck effect



Type	Common name	Positive element[a]	Negative element[a]	Recommended service environment(s)	Maximum service temp. (°C)
B	Platinum-rhodium/ platinum-rhodium	70 Pt–30 Rh	94 Pt–6 Rh	Oxidizing Vacuum Inert	1,700
E	Chromel/constantan	90 Ni–9 Cr	44 Ni–55 Cu	Oxidizing	870
J	Iron/constantan	Fe	44 Ni–55 Cu	Oxidizing Reducing	760
K	Chromel/alumel	90 Ni–9 Cr	94 Ni–Al, Mn, Fe, Si, Co	Oxidizing	1,260
R	Platinum/platinum-rhodium	87 Pt–13 Rh	Pt	Oxidizing Inert	1,480
S	Platinum/platinum-rhodium	90 Pt–10 Rh	Pt	Oxidizing Inert	1,480
T	Copper/constantan	Cu	44 Ni–55 Cu	Oxidizing Reducing	370

Source: Data from *Metals Handbook*, 9th ed., Vol. 3, American Society for Metals, Metals Park, OH, 1980.
[a] Alloy compositions expressed as weight percents.