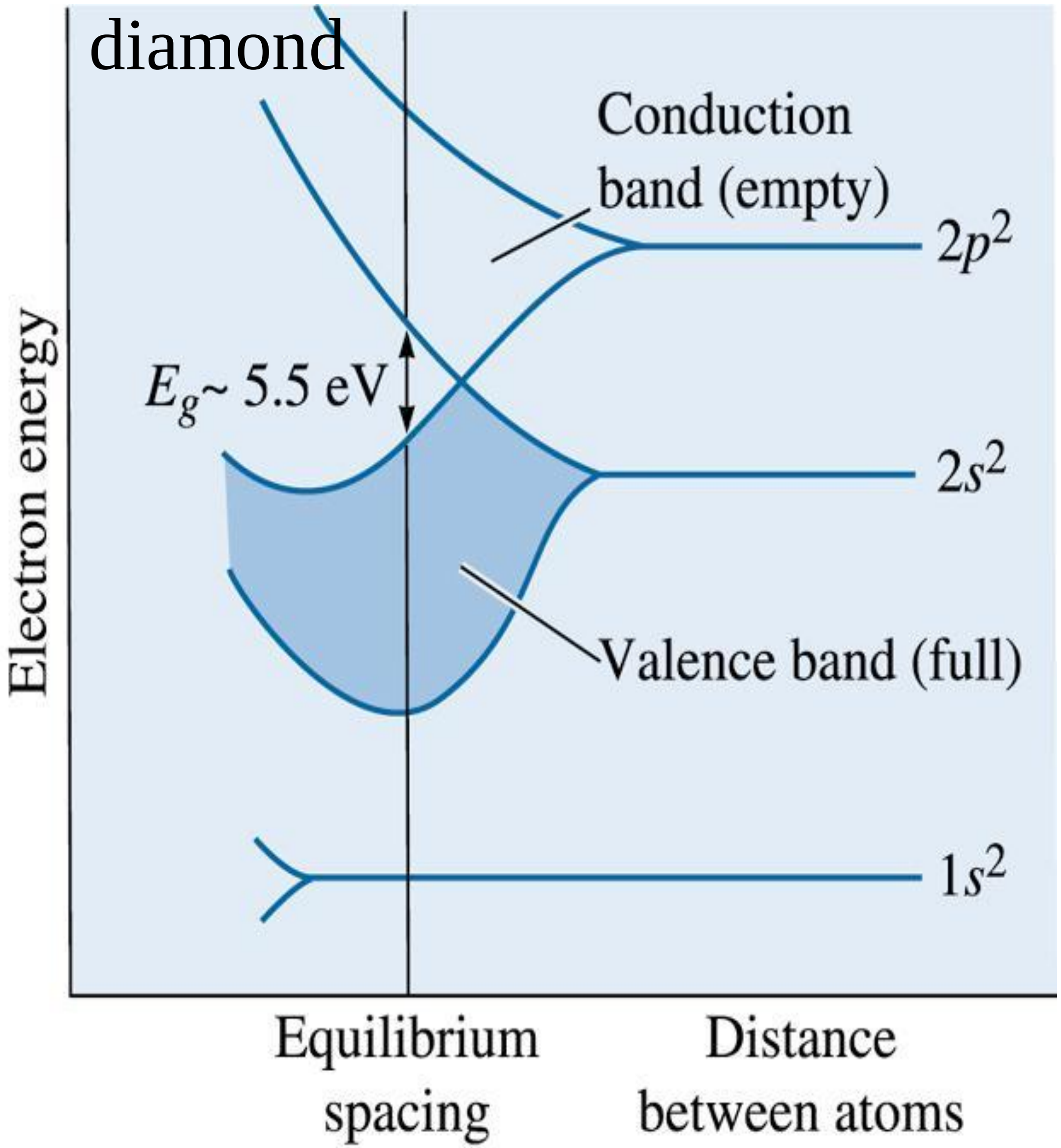
CHAPTER 18: ELECTRICAL PROPERTIES

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

ENERGY BAND FOR INSULATORS



CONDUCTIVITY OF INSULATORS

Table 18.3 Typical Room-Temperature Electrical Conductivities for 13 Nonmetallic Materials

Material	*Electrical Conductivity* $[(\Omega\text{-}m)^{-1}]$
Graphite	3×10^4–2×10^5
Ceramics	
Concrete (dry)	10^{-9}
Soda–lime glass	10^{-10}–10^{-11}
Porcelain	10^{-10}–10^{-12}
Borosilicate glass	$\sim 10^{-13}$
Aluminum oxide	$<10^{-13}$
Fused silica	$<10^{-18}$
Polymers	
Phenol-formaldehyde	10^{-9}–10^{-10}
Polymethyl methacrylate	$<10^{-12}$
Nylon 6,6	10^{-12}–10^{-13}
Polystyrene	$<10^{-14}$
Polyethylene	10^{-15}–10^{-17}
Polytetrafluoroethylene	$<10^{-17}$

CONDUCTION IN IONIC MATERIALS

- **charge carrier: cation, anion, electron**
- **total conductivity**

  - $\sigma_{\text{total}} = \sigma_{\text{ionic}} + \sigma_{\text{electronic}}$

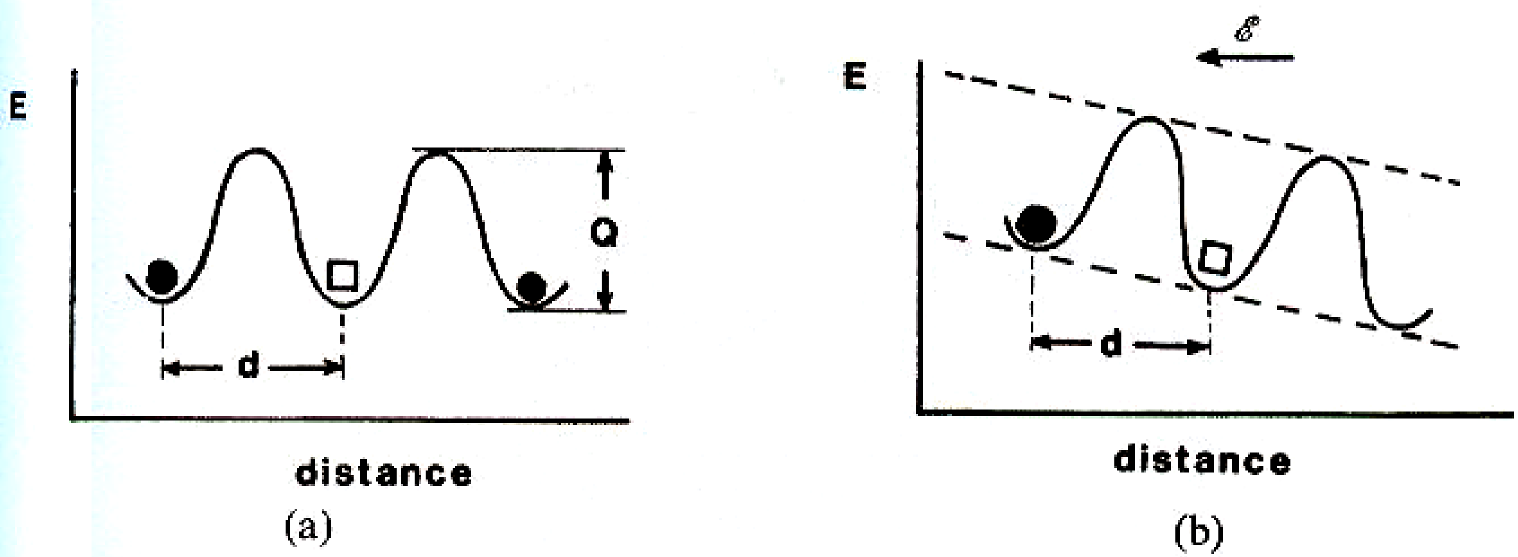


Figure 9.8. Schematic representation of a potential barrier, which an ion (●) has to overcome to exchange its site with a vacancy (□). (a) Without an external electric field; (b) with an external electric field. d = distance between two adjacent, equivalent lattice sites; Q = activation energy.

CONDUCTION IN IONIC MATERIALS

- $\mu_{ion} = \frac{q}{kT} D_{ion}$ (Einstein relationship)

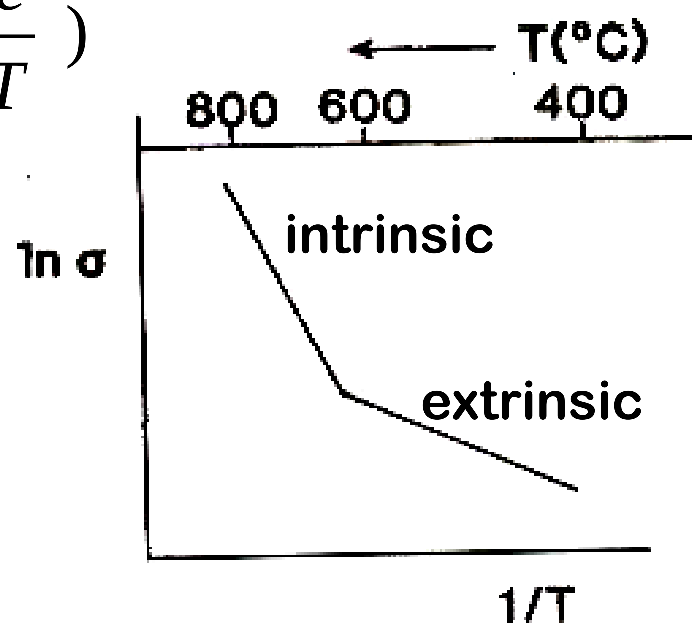
- temperature dependence of ionic conductivity

$$\sigma_{ion}(T) = N_{ion} q_{ion} \mu_{ion} = N_{ion} q_{ion} \frac{q}{kT} D_{ion} = \frac{N_{ion} q_{ion}^2 D_o}{kT} \exp(-\frac{Q'}{kT})$$

$$= \sigma_o \exp(-\frac{Q}{kT}) \quad (\because N_{ion} \sim e,\ \mu_{ion} \sim \frac{e}{T})$$

- transference number

$$t_{cat} = \frac{\sigma_{cat}}{\sigma_{total}} = \frac{N_{cat} q_{cat} \mu_{cat}}{\sigma_{total}}$$



IONIC CONDUCTIVITY

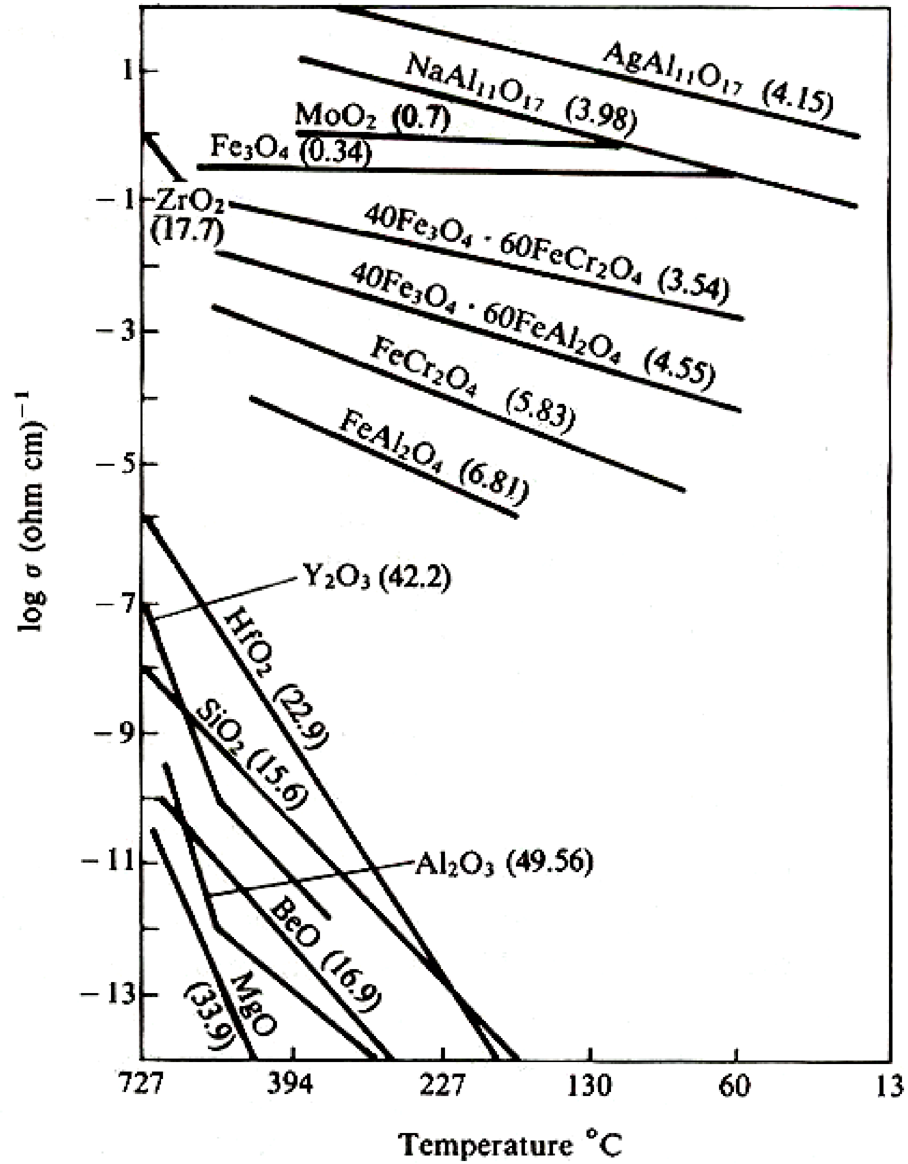


FIGURE 4.3 Temperature dependence of conductivity for several oxides with activation energy in Kcal/mol shown in brackets ( ).

IONIC CONDUCTION VS. DIFFUSION

- **activation energy**

TABLE 10.2–5 A comparison of the activation energies for ionic conduction and the diffusion of Na^{+1} in a series of silicate glasses.

Composition (Mol %)					Activation energy (kJ/mol)	
Na_2O	CaO	Al_2O_3	SiO_2	GeO_2	Diffusion (Na^+)	Conduction
33.3	—	—	66.7	—	54–59	59–67
25.0	—	—	—	75.0	71–75	67–75
15.7	—	12.1	72.2	—	68.6	65.3
11.0	—	16.1	72.9	—	65.3	63.2
15.9	11.9	—	72.2	—	92.0	87.0
14.5	12.3	5.8	67.4	—	84.5	81.6

Source: L. L. Hench and J. K. West, *Principles of Electronic Ceramics*. Copyright © 1990 by John Wiley & Sons. Reprinted by permission of John Wiley & Sons, Inc.

IONIC MATERIALS

- **transference number**

Compound	Temperature (°C)	t_{cation}	t_{anion}	$t_{electron/hole}$
NaCl	400	1.0	0	0
	600	0.95	0.05	0
KCl	435	0.96	0.04	0
	600	0.88	0.12	0
KCl + 0.02% $CaCl_2$	430	0.99	0.01	0
	600	0.99	0.01	0
AgCl	20–350	1.0	0	0
AgBr	20–350	1.0	0	0
BaF_2	500	0	1.0	0
PbF_2	200	0	1.0	0
CuCl	20	0	0	1.0
	366	1.0	0	0
ZrO_2 + 7% CaO	> 700	0	1.0	10^{-4}
$Na_2O \cdot 11Al_2O_3$	< 800	1.0 (Na^+)	0	$< 10^{-6}$
FeO	800	10^{-4}	0	1.0
ZrO_2 + 18% CeO_2	1500	0	0.52	0.48
ZrO_2 + 50% CeO_2	1500	0	0.15	0.85
$Na_2O \cdot CaO \cdot SiO_2$ glass	—	1.0 (Na^+)	0	0

IONIC CONDUCTOR

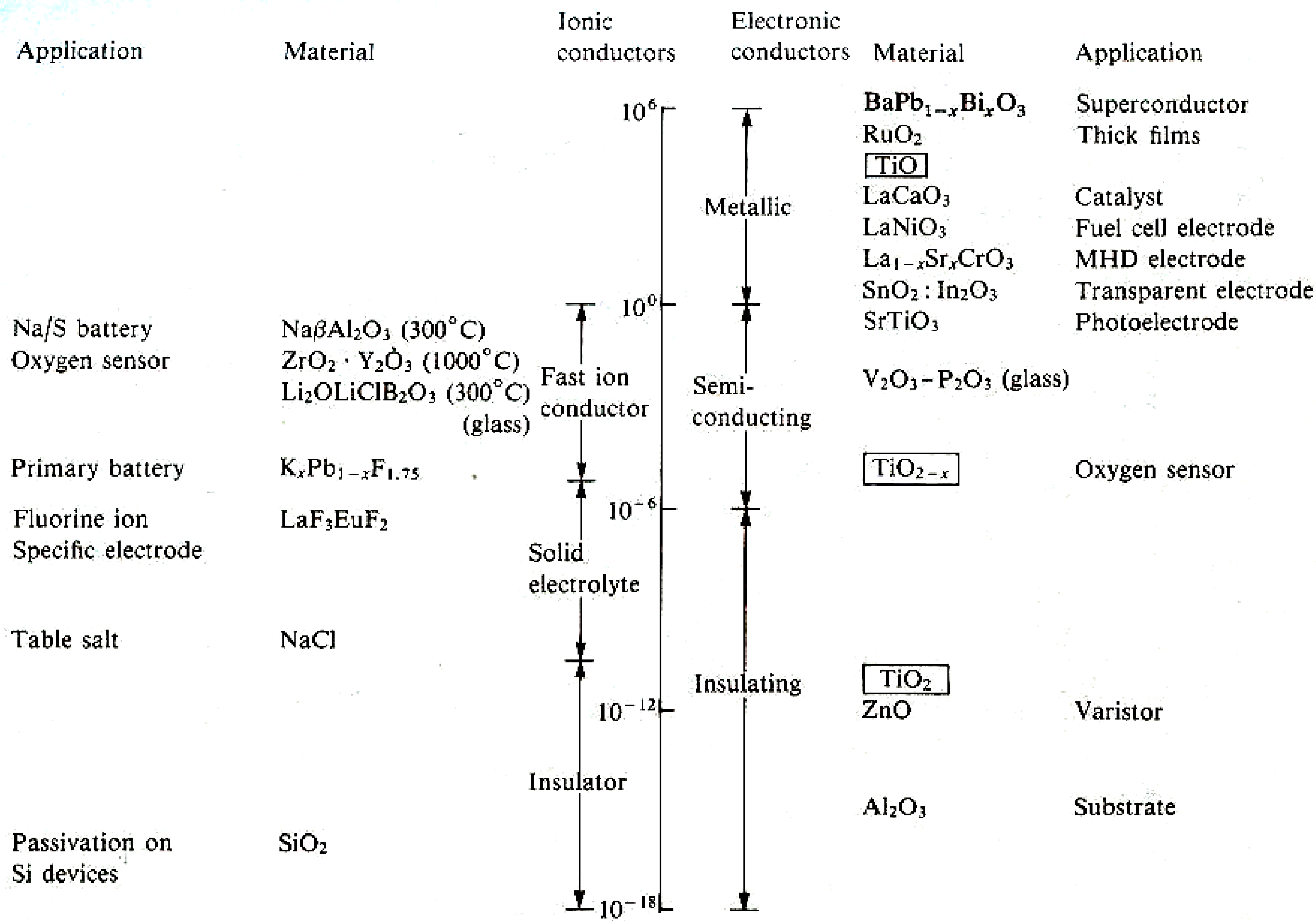
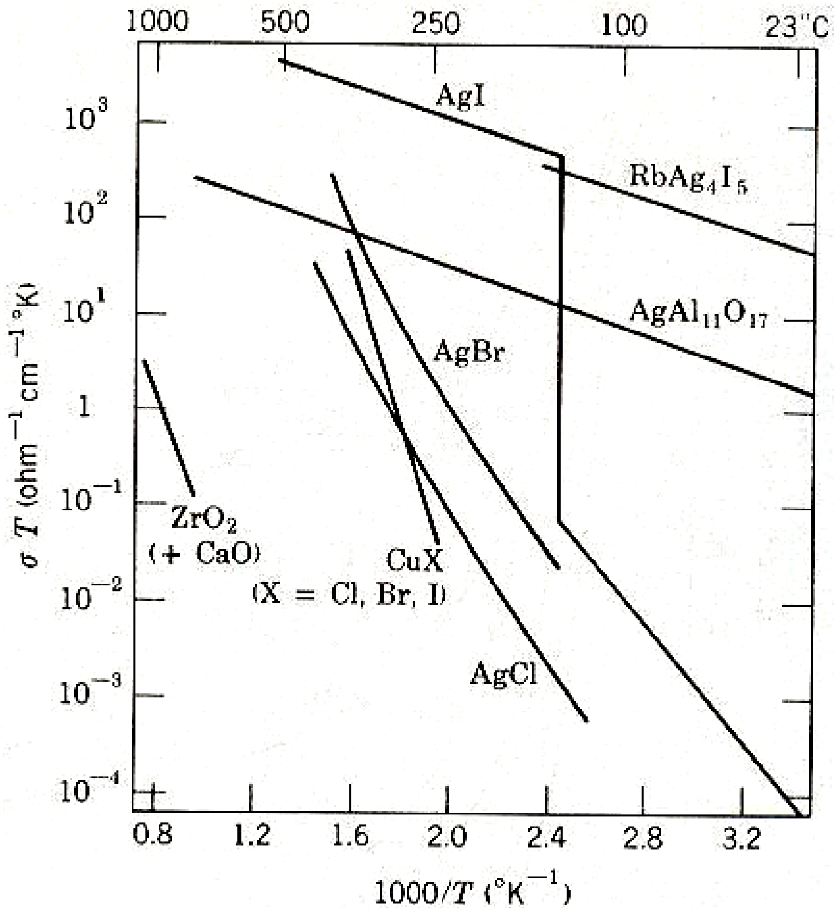


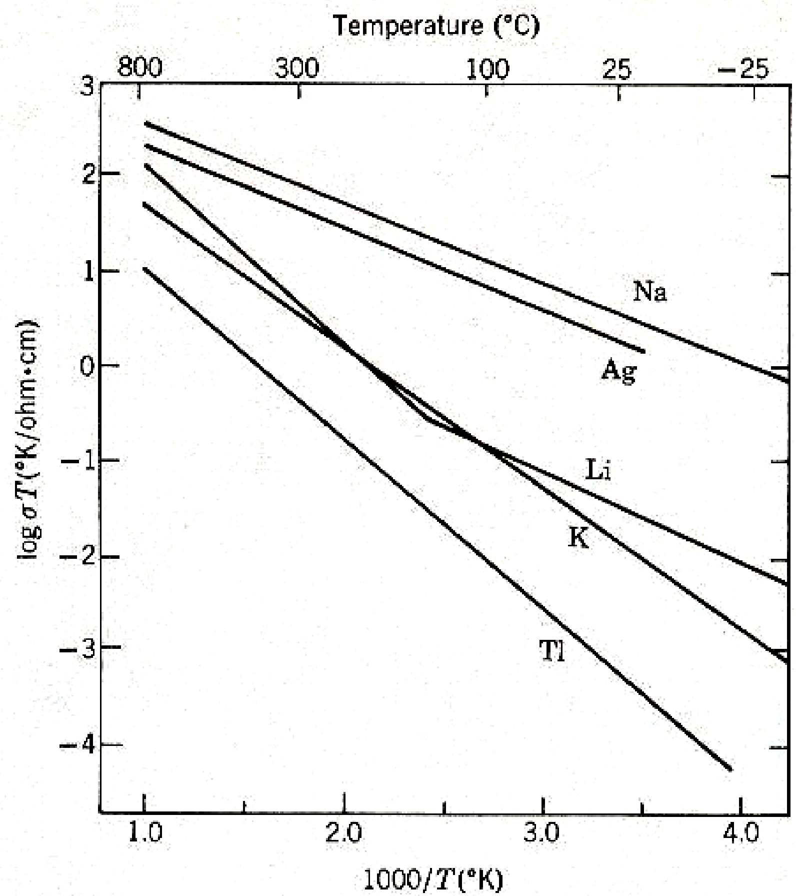
FIGURE 4.13 Fast ion conductors. Logarithmic scale of conductivity for ionic vs. electronic materials.

Hench and West, Principles of Electronic Ceramics

FAST ION CONDUCTOR



Conductivity of some highly conducting solid electrolytes.



Electrical conductivity for various β-aluminas. From R. A. Huggins.

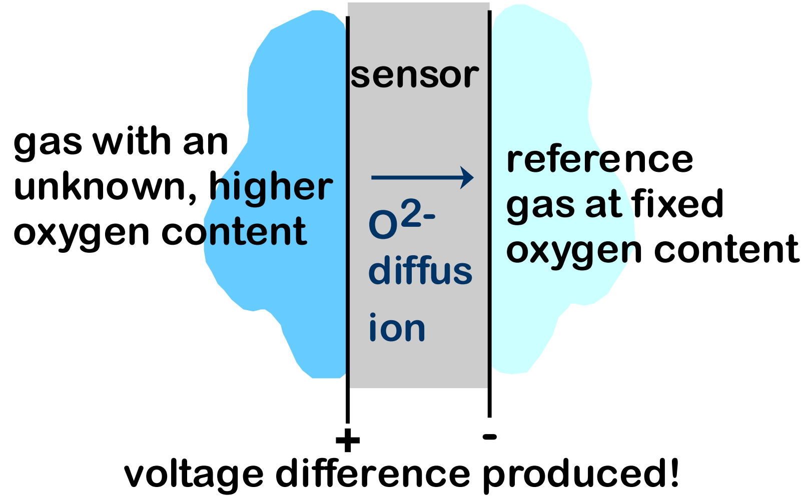
FAST ION CONDUCTOR

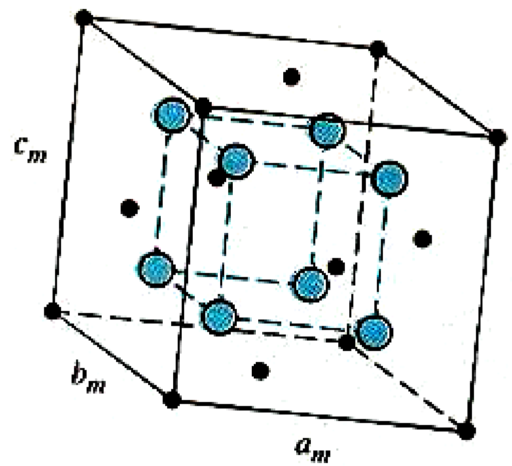
- **ZrO_2- fluorite structure**

Y_2O_3 stabilized ZrO_2

$$Y_2O_3 \xrightarrow{ZrO_2} 2Y_{Zr}^{'} + 3O_o^x + V_o^{\bullet\bullet}$$

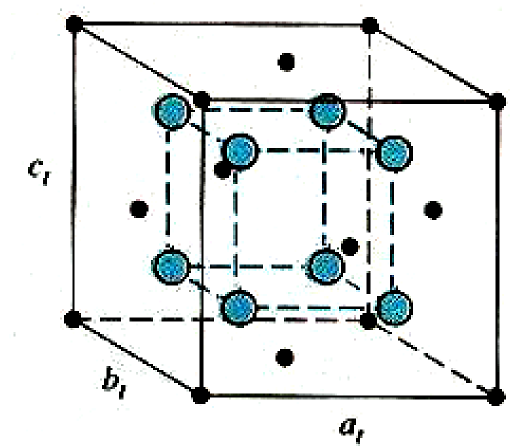
$$[Y_{Zr}^{'}]=2[V_o^{\bullet\bullet}]$$





Monoclinic

$a_m = 0.5156$ nm
$b_m = 0.5191$ nm
$c_m = 0.5304$ nm
$\beta = 98.9°$

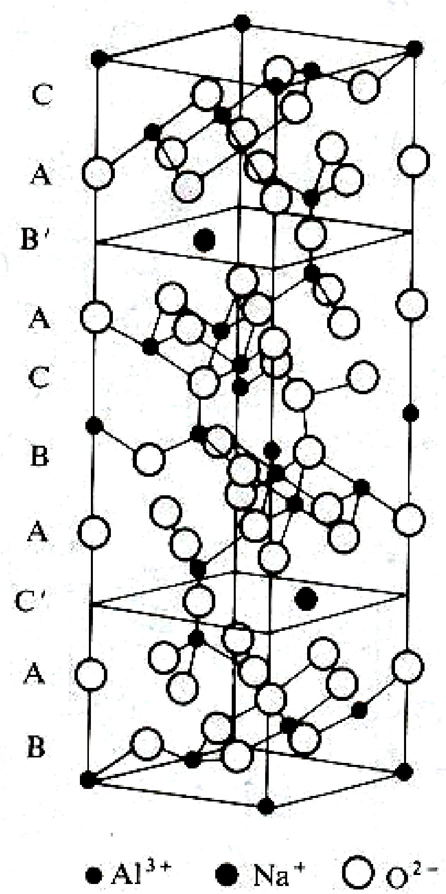


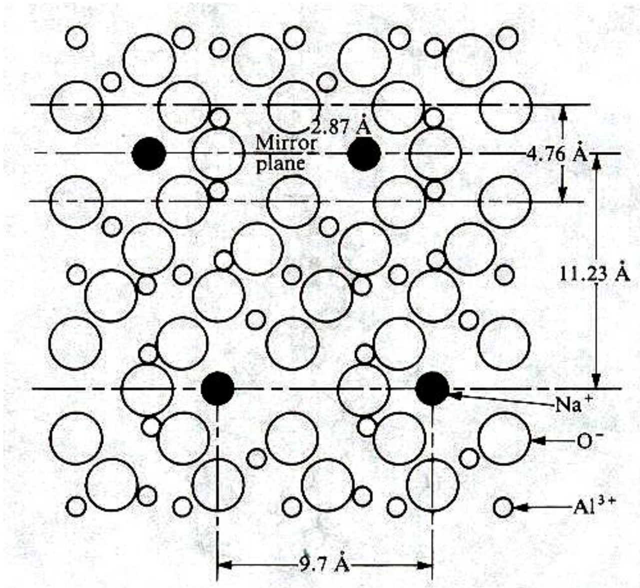
Tetragonal

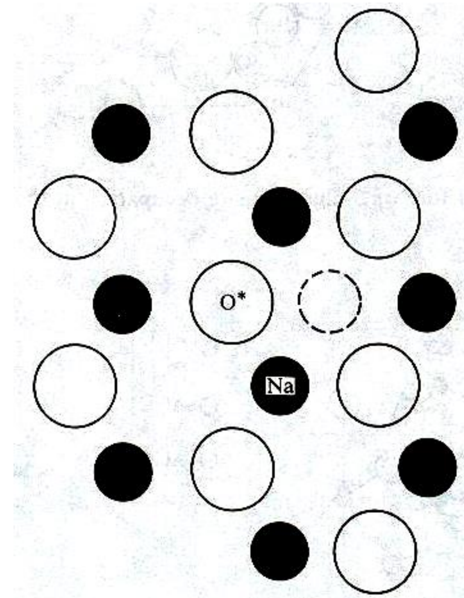
$a_t = 0.5094$ nm
$b_t = 0.5177$ nm
$c_t = a_t$

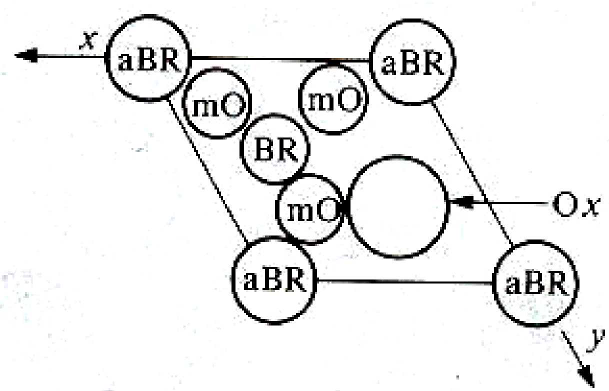
FAST ION CONDUCTOR

- β-alumina ($NaAl_{11}O_{17}$)



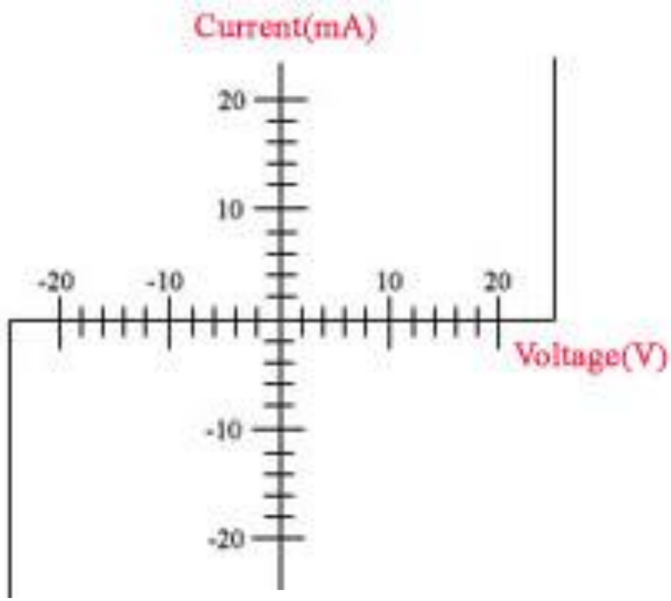


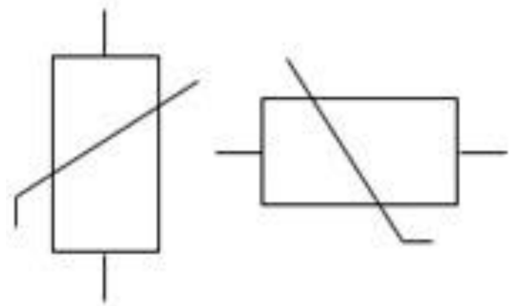


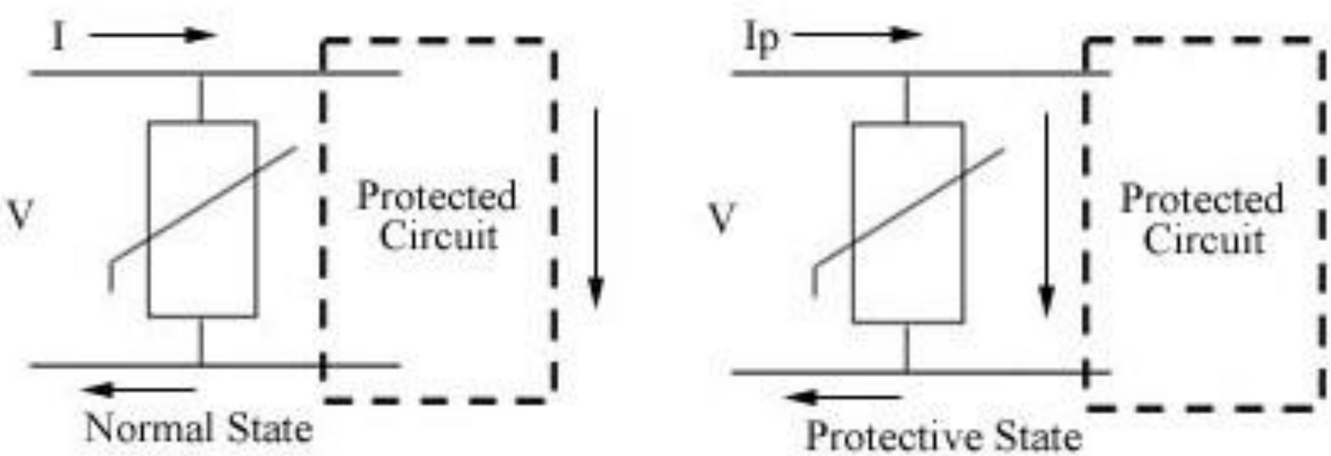


NON-LINEAR

- **varistor- surge protection**



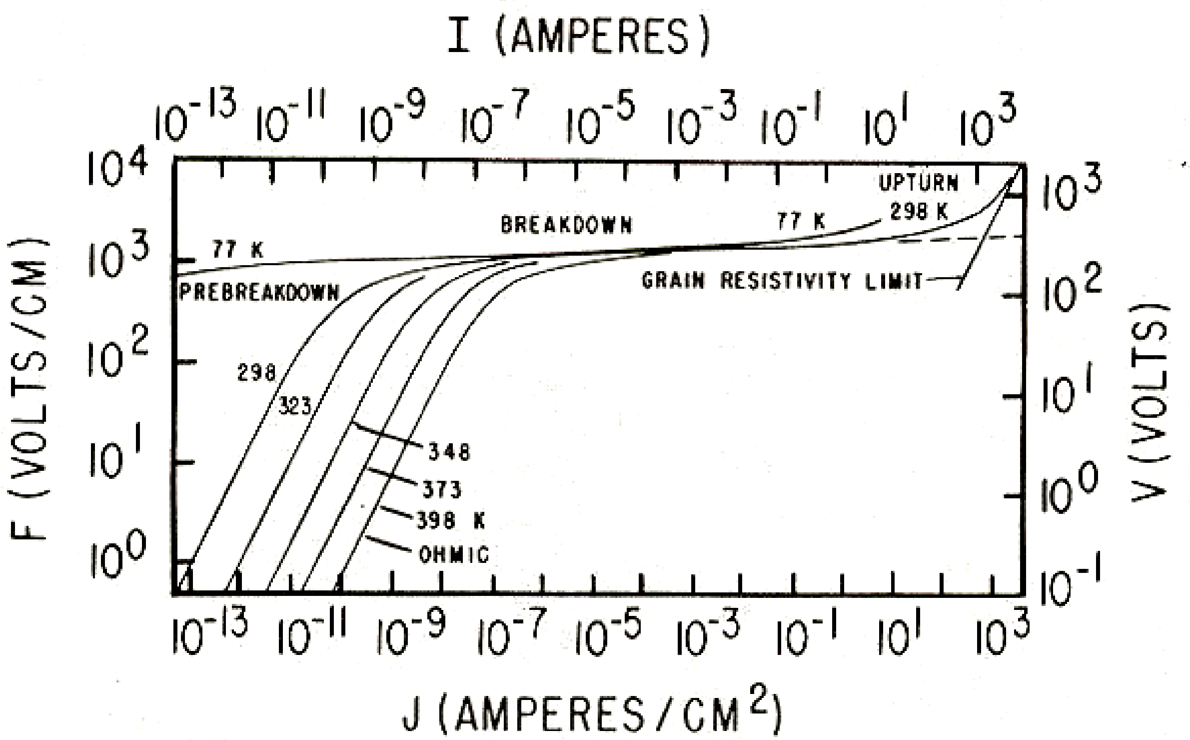


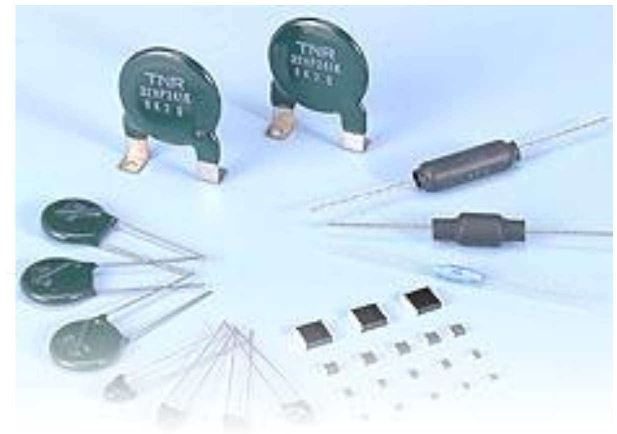


www.phonda.com.tw/ varistor.htm

NON-LINEAR

- varistor- ZnO (doped with Bi_2O_3)





$$I = kV^{\alpha}$$

$$\alpha = 25 \sim 50$$

FIGURE 8 Current-voltage characteristics of a metal oxide varistor at 77 K and for a small range of temperatures near 300 K. The exponent α equals the inverse slope of the curve and is a measure of device non-linearity.

ZnO VARISTOR

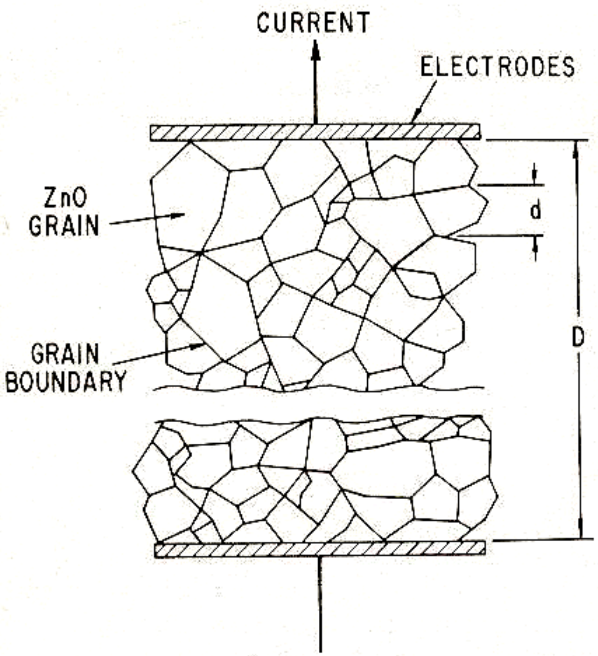


FIGURE 10 Schematic depiction of the microstructure of a ZnO varistor. Grains of conducting ZnO, average size d, are completely surrounded by a segregation layer enriched in some of the additive cations (few atomic layers thick). Electrodes are attached and current flows as indicated.

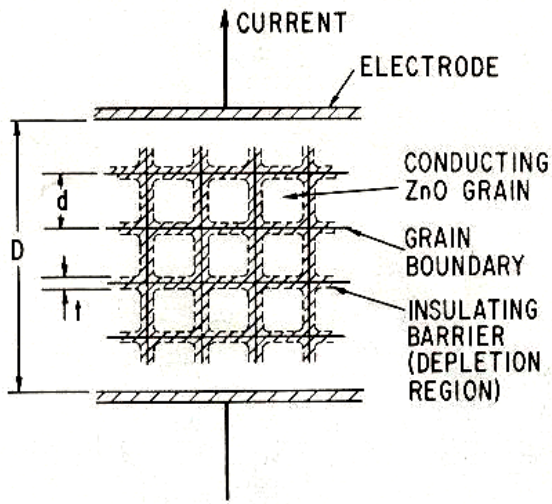


FIGURE 12 "Block model" of a ZnO varistor having grain size d (≃ 10 μm) and intergranular depletion barrier thickness t (≃ 100 nm). D is the electrode separation. (Not to scale.)

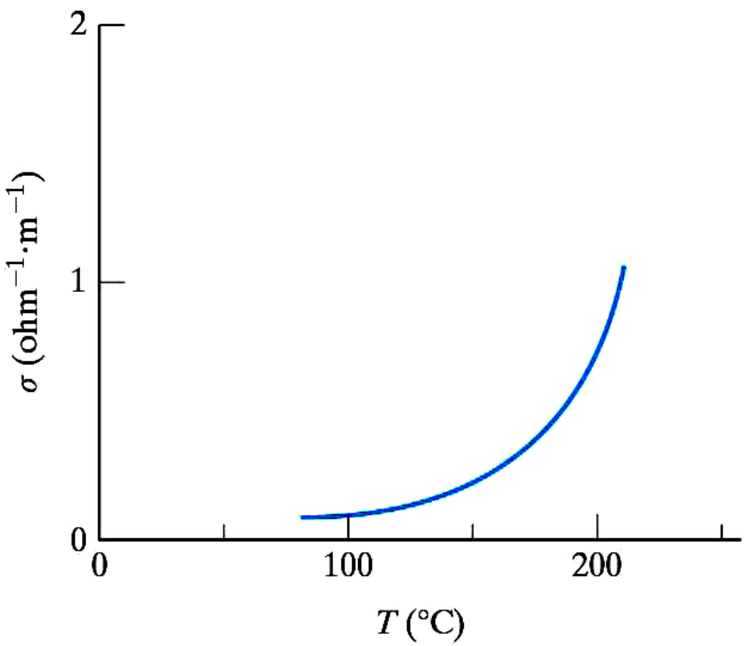
SEMICONDUCTOR

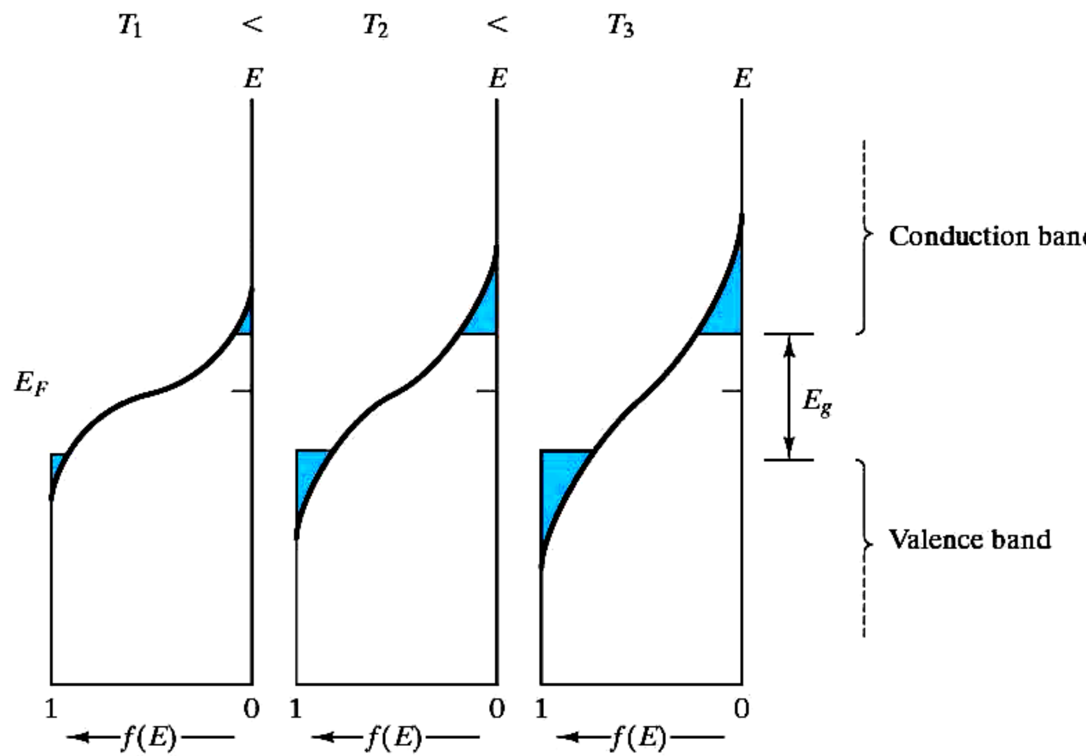
- Bandgap: less than 2 eV
- Intrinsic
  Extrinsic

Table 18.2 Band Gap Energies, Electron and Hole Mobilities, and Intrinsic Electrical Conductivities at Room Temperature for Semiconducting Materials

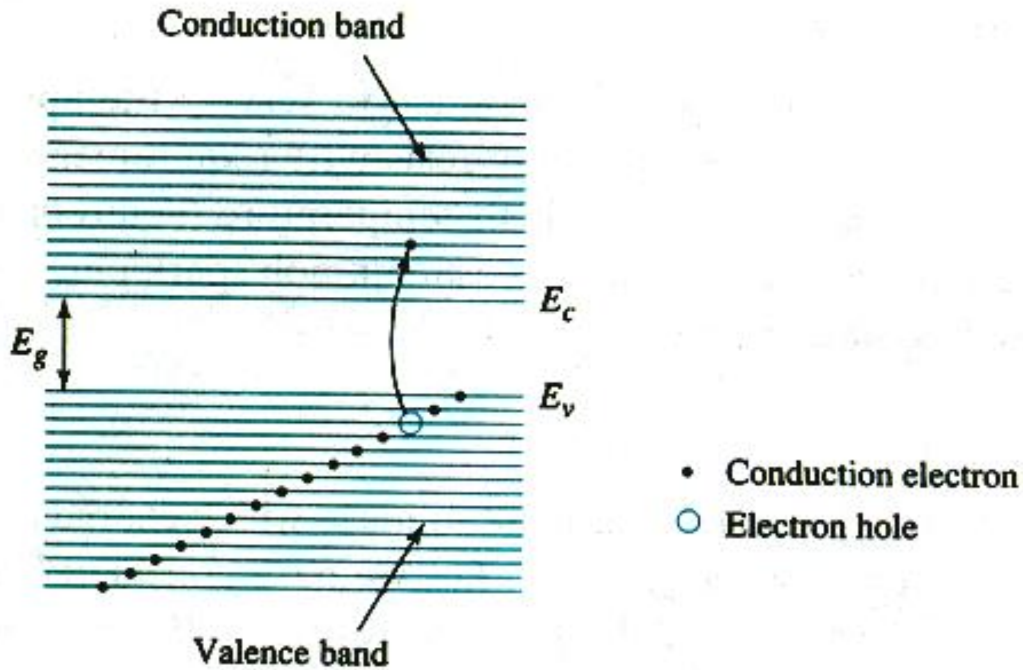
Material	*Band Gap* (eV)	*Electrical Conductivity* $[(\Omega\text{-}m)^{-1}]$	*Electron Mobility* $(m^2/V\text{-}s)$	*Hole Mobility* $(m^2/V\text{-}s)$
		Elemental		
Si	1.11	4×10^{-4}	0.14	0.05
Ge	0.67	2.2	0.38	0.18
		III–V Compounds		
GaP	2.25	—	0.03	0.015
GaAs	1.42	10^{-6}	0.85	0.04
InSb	0.17	2×10^{4}	7.7	0.07
		II–VI Compounds		
CdS	2.40	—	0.03	—
ZnTe	2.26	—	0.03	0.01

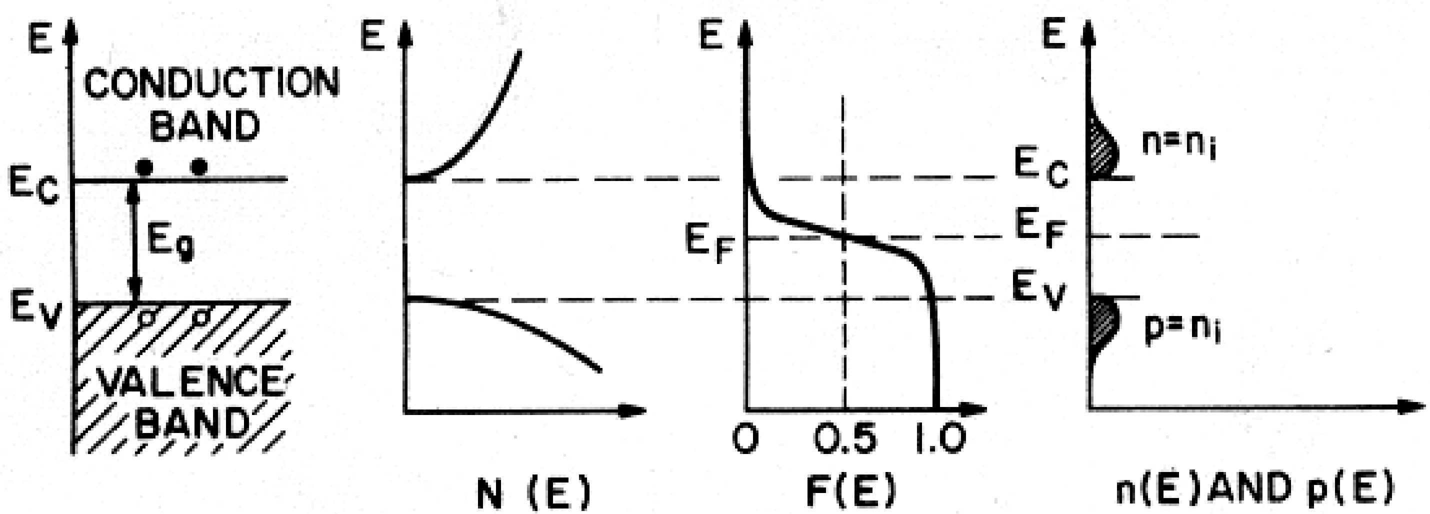
INTRINSIC SEMICONDUCTOR



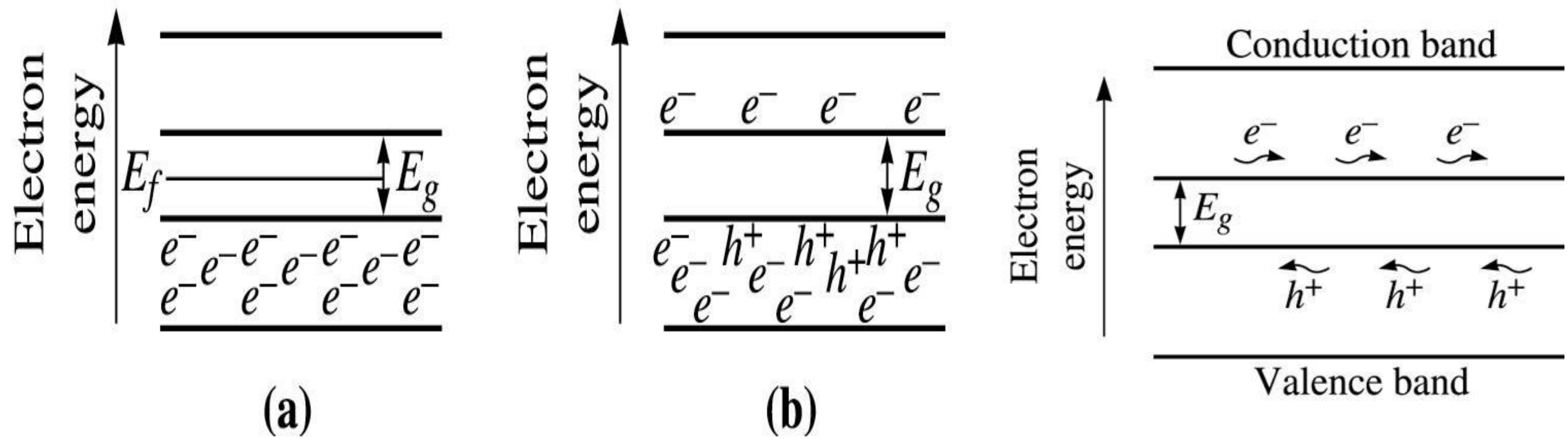


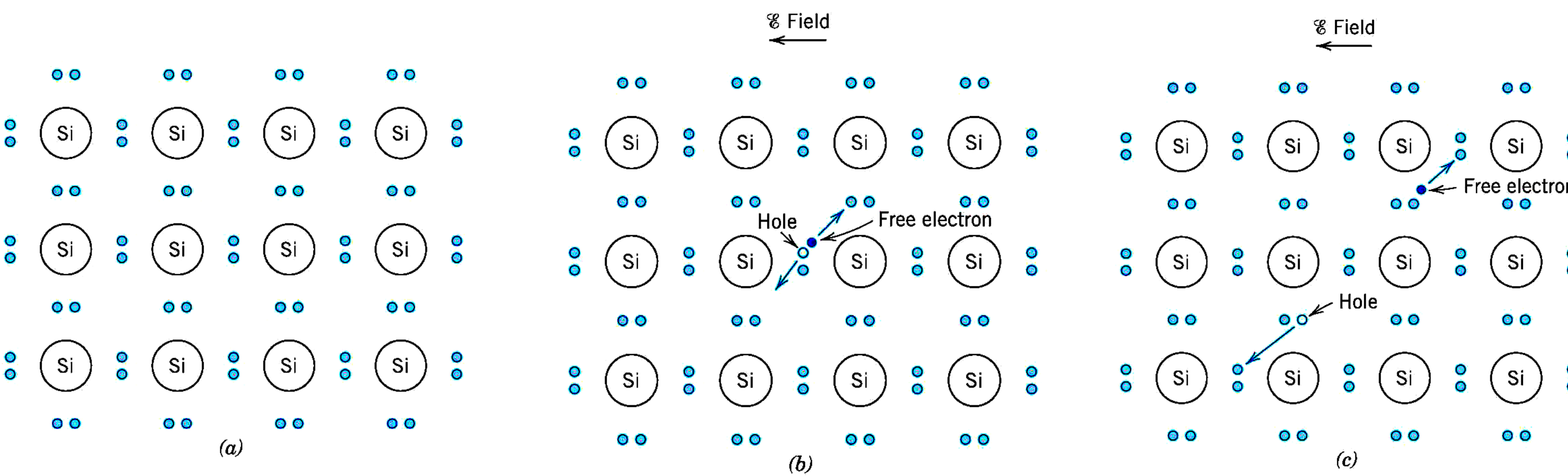
INTRINSIC SEMICONDUCTOR





INTRINSIC SEMICONDUCTOR





INTRINSIC SEMICONDUCTOR

$$\sigma = n|e|\mu_e + p|e|\mu_h = |e|(n\mu_e + p\mu_h)$$

$$n = p = n_i = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_e^* m_e^*)^{3/4}\, \mathrm{e}^{-E_g/2kT}$$

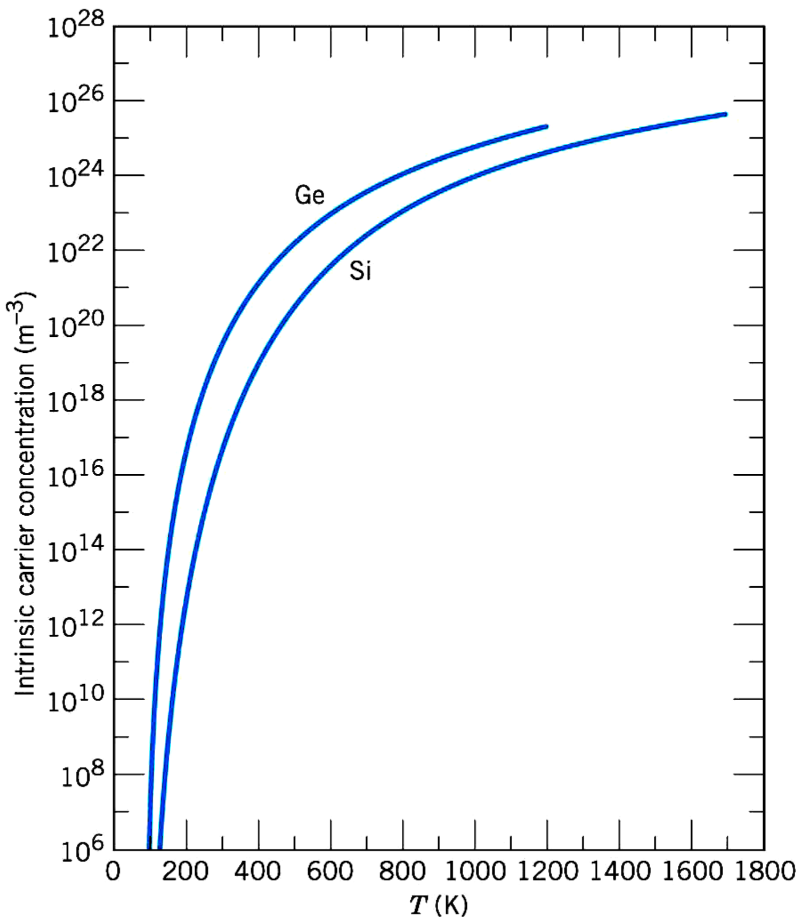
$$= n_o\, \mathrm{e}^{-E_g/2kT}$$

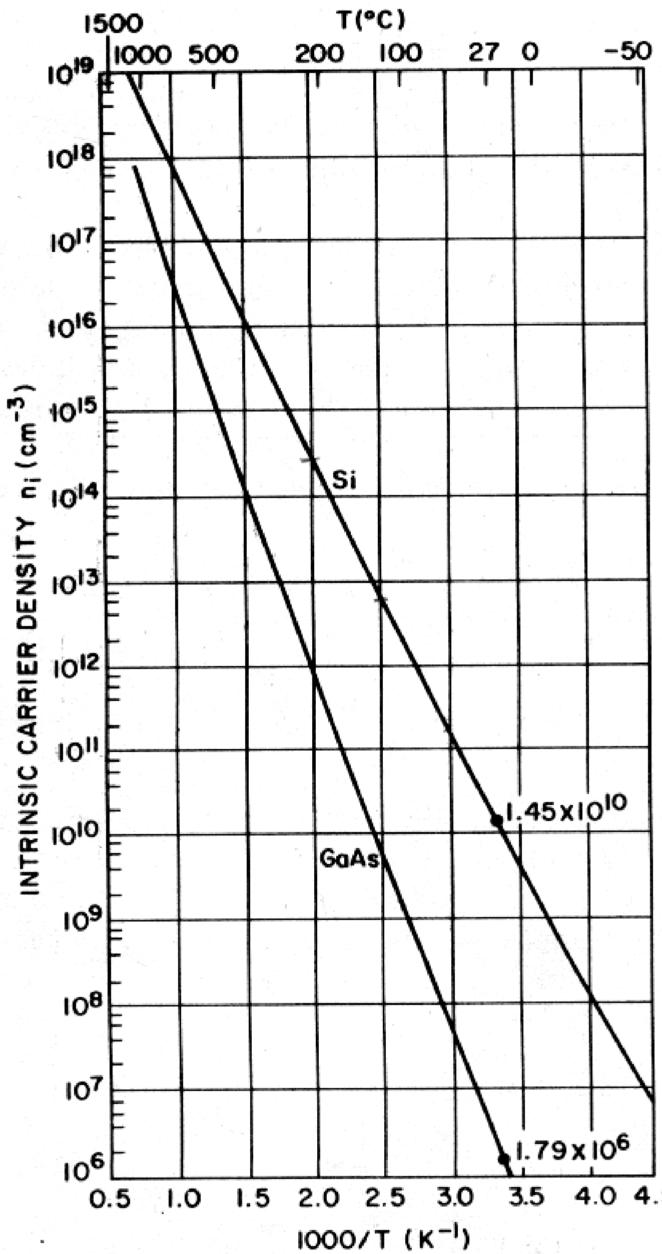
$$\mu_e \sim T^{-3/2}$$

$$\sigma = n_o|e|(\mu_e + \mu_h)e^{-E_g/2kT} = \sigma_o e^{-E_g/2kT}$$

$$\ln\sigma = \ln\sigma_o - \frac{E_g}{2k}\frac{1}{T}$$

INTRINSIC SEMICONDUCTOR





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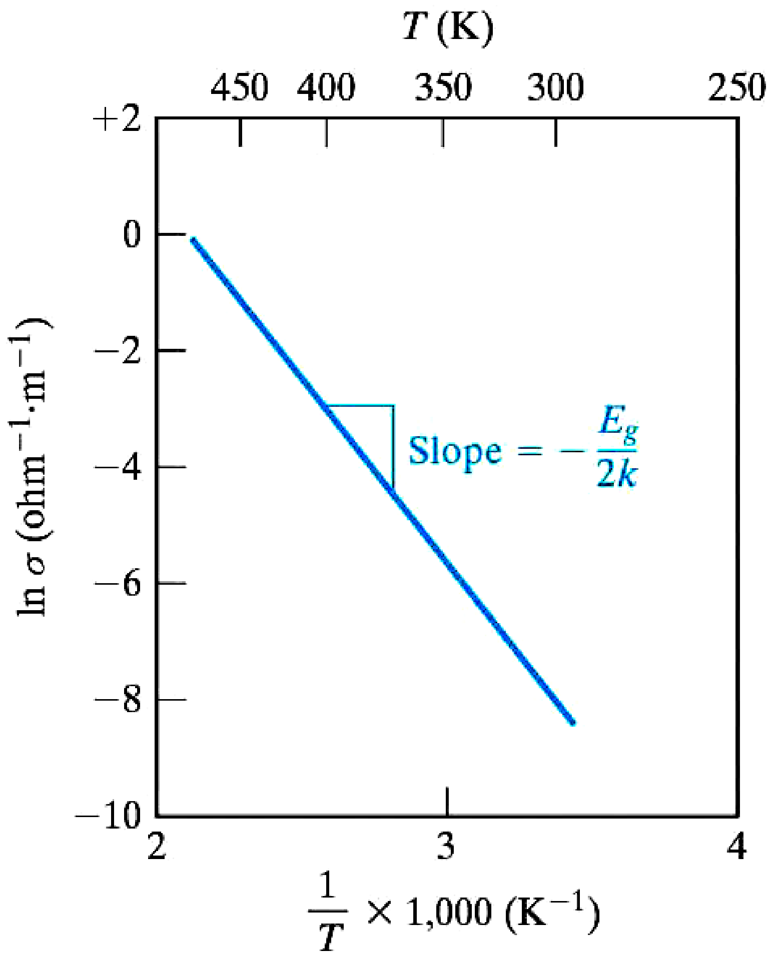
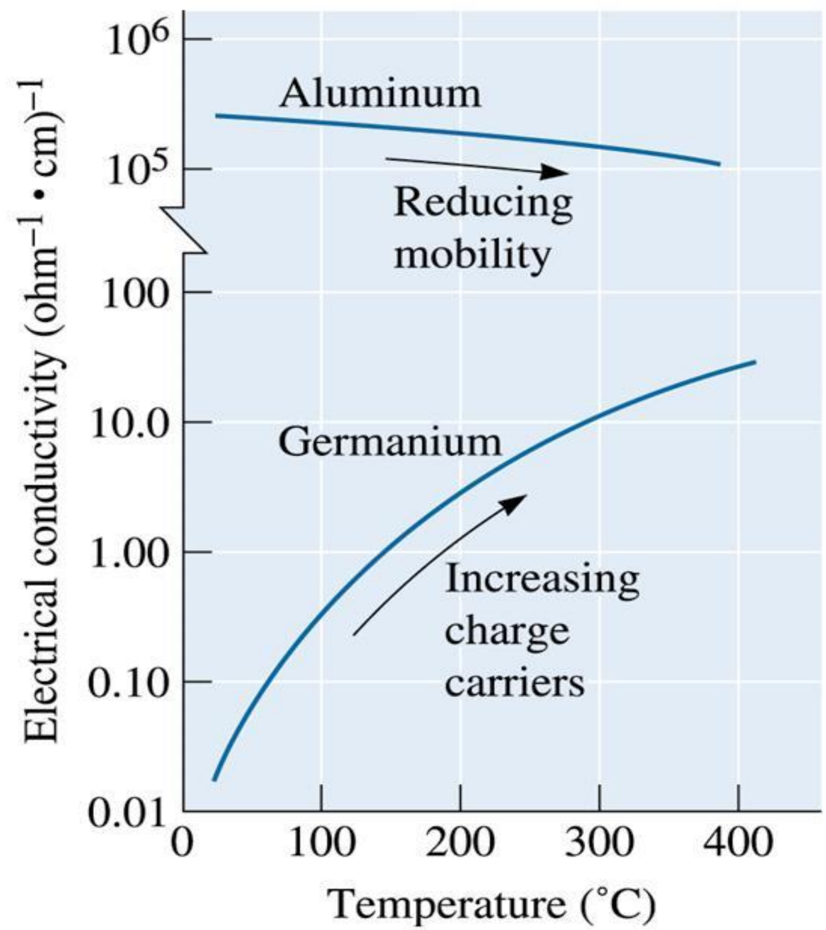


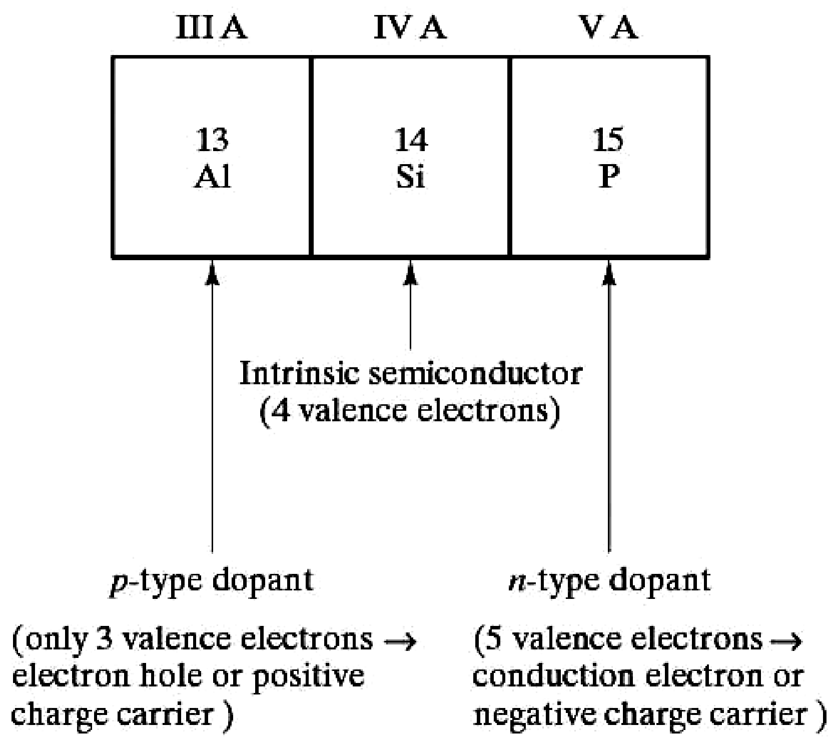


INTRINSIC SEMICONDUCTOR

Table 18-6 *Properties of commonly encountered semiconductors*

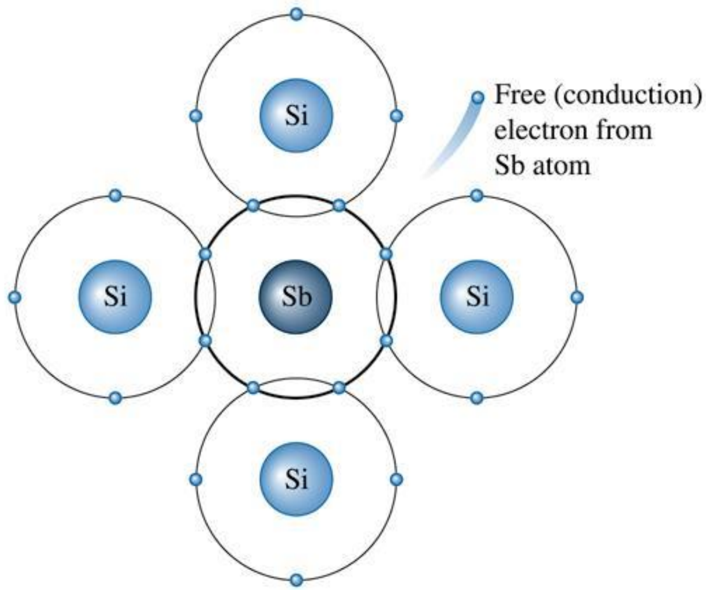
Semiconductor	Bandgap eV	Mobility of Electrons (μ_n) $\frac{cm^2}{V\text{-}s}$	Mobility of Holes (μ_p) $\frac{cm^2}{V\text{-}s}$	Dielectric Constant (k)	Resistivity $\Omega \cdot cm$	Density $\frac{gm}{cm^3}$	Melting Temperature °C
Silicon (Si)	1.11	1350	480	11.8	2.5×10^5	2.33	1415
Amorphous Silicon (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

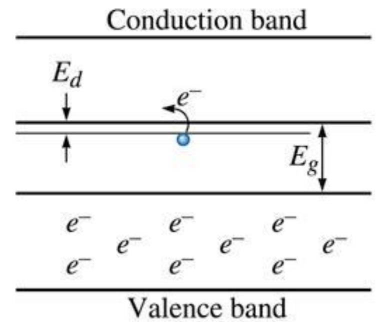
EXTRINSIC SEMICONDUCTOR

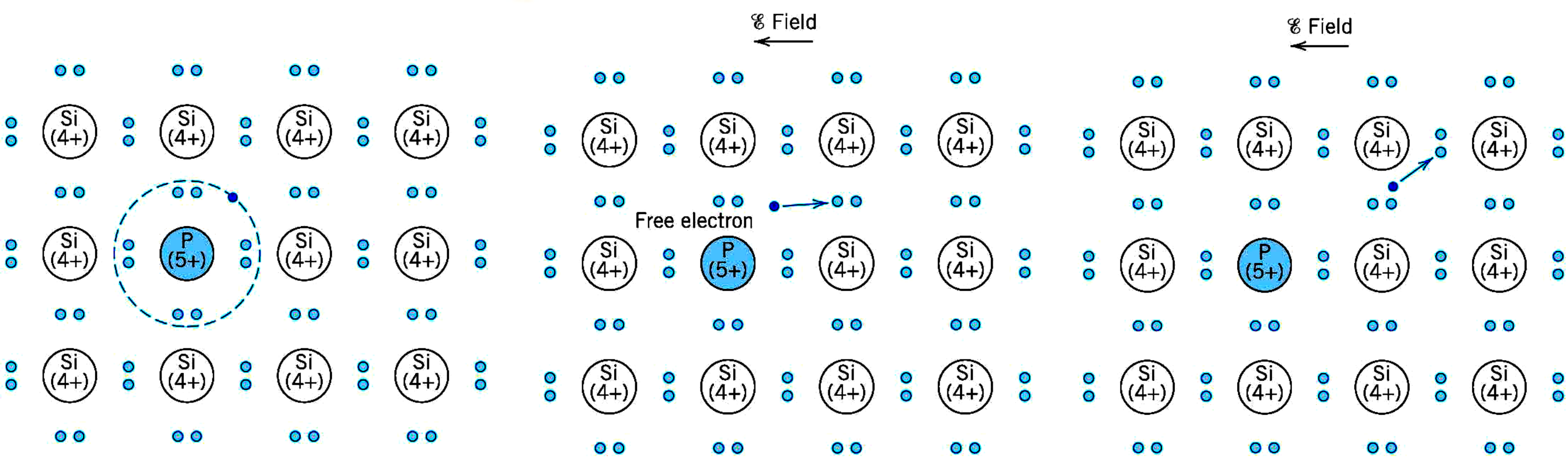


- **Intrinsic**:
  # electrons = # holes (n = p)
- **Extrinsic**:
  --n $\neq$ p
- **N-type** Extrinsic: (n >> p)
- **P-type** Extrinsic: (p >> n)

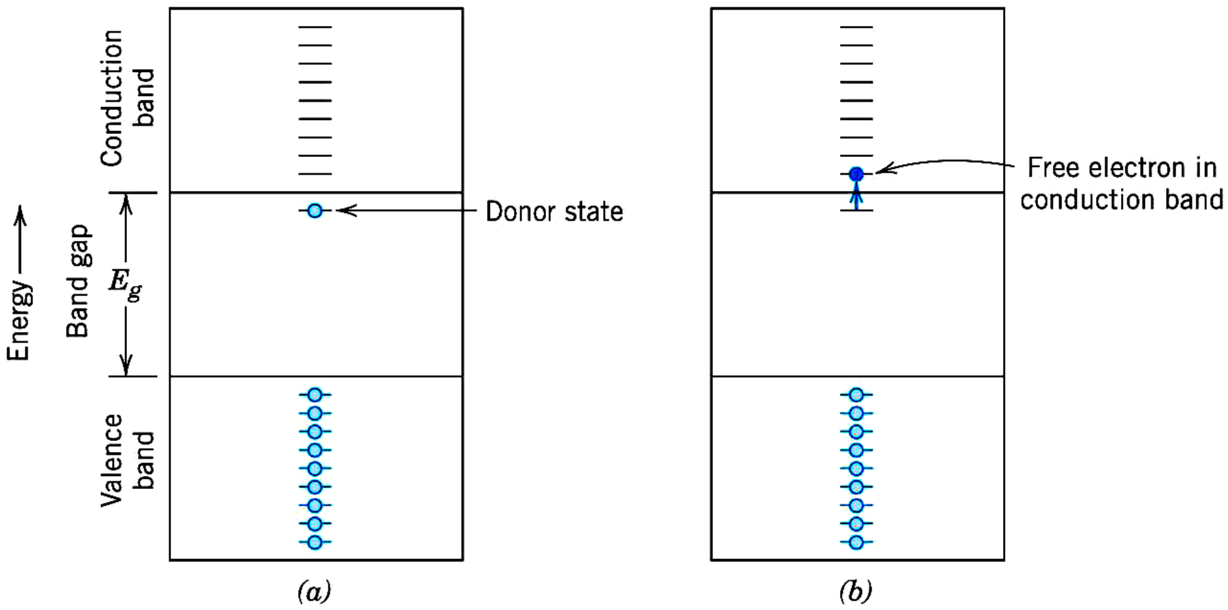
N-TYPE SEMICONDUCTOR

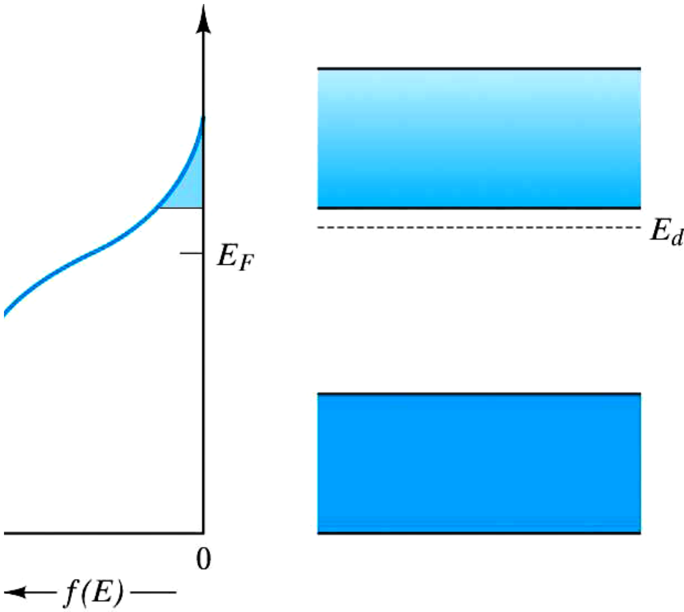




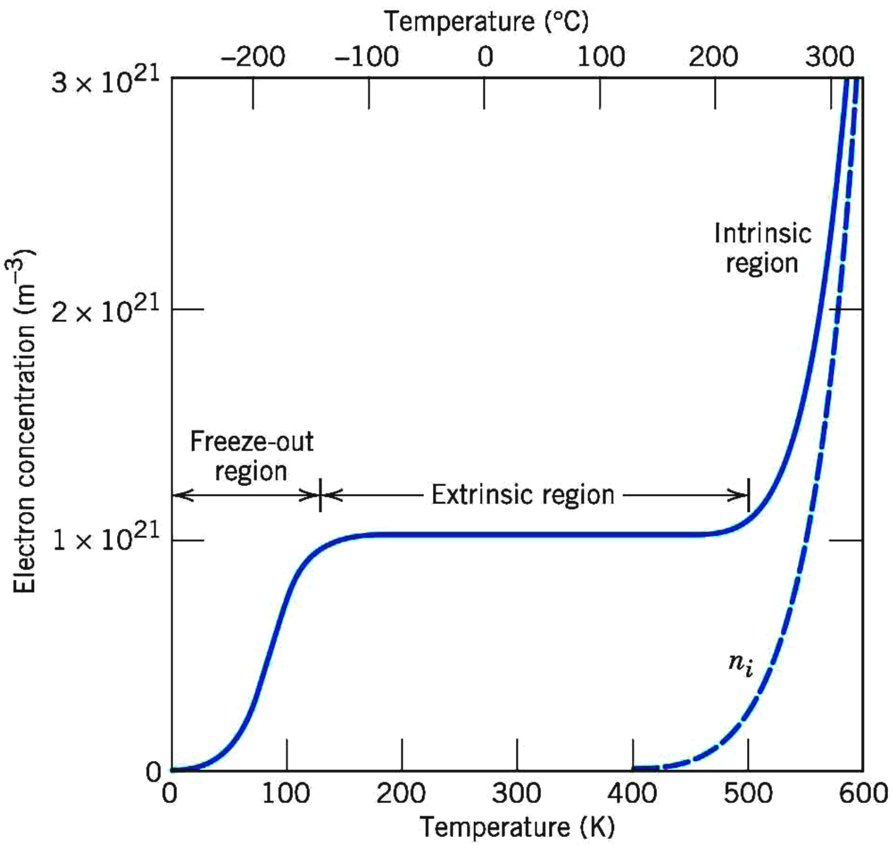


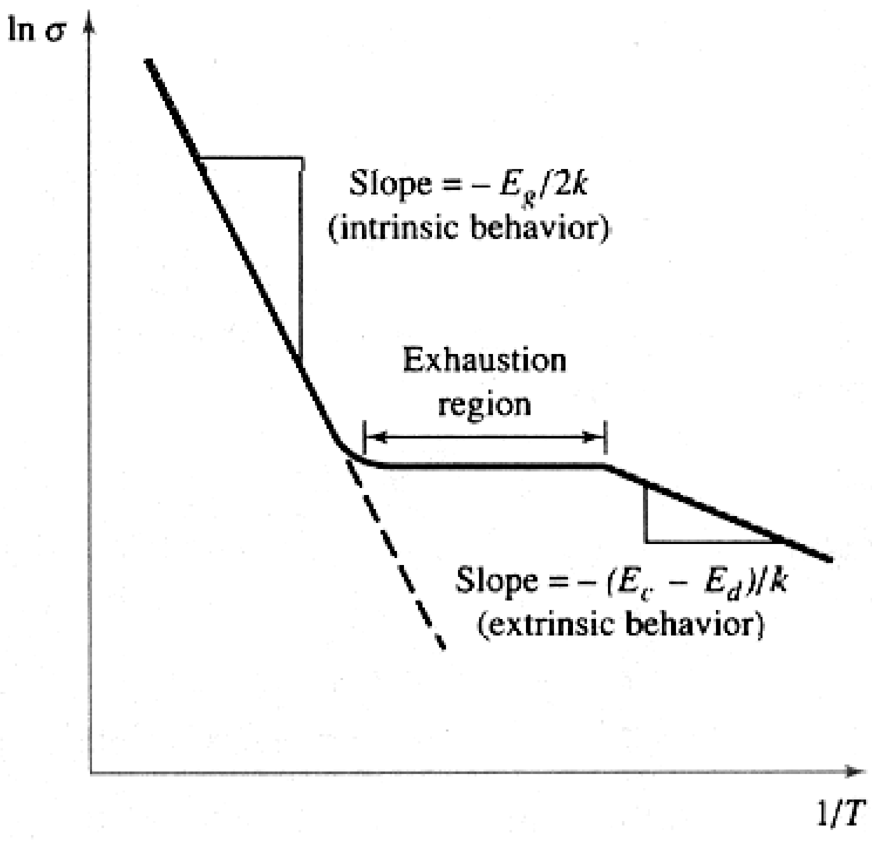
N-TYPE SEMICONDUCTOR



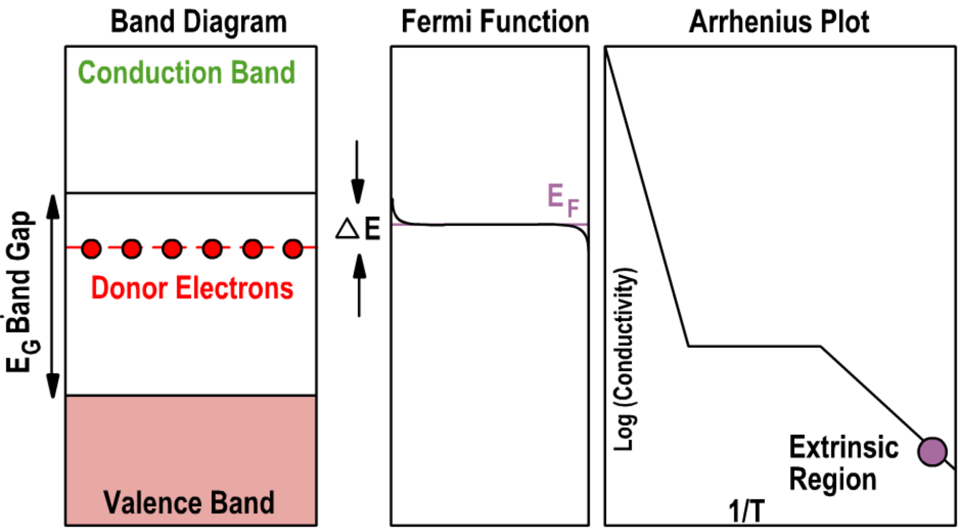


N-TYPE SEMICONDUCTOR

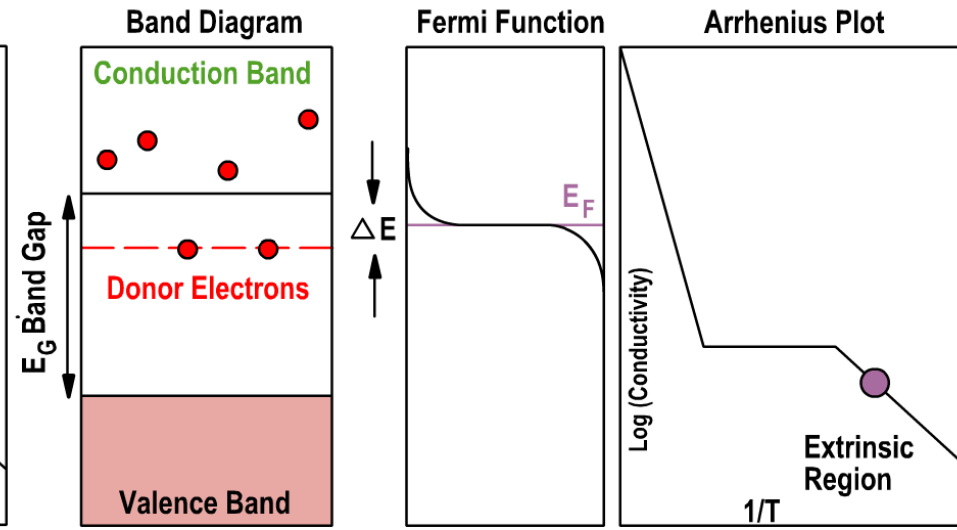




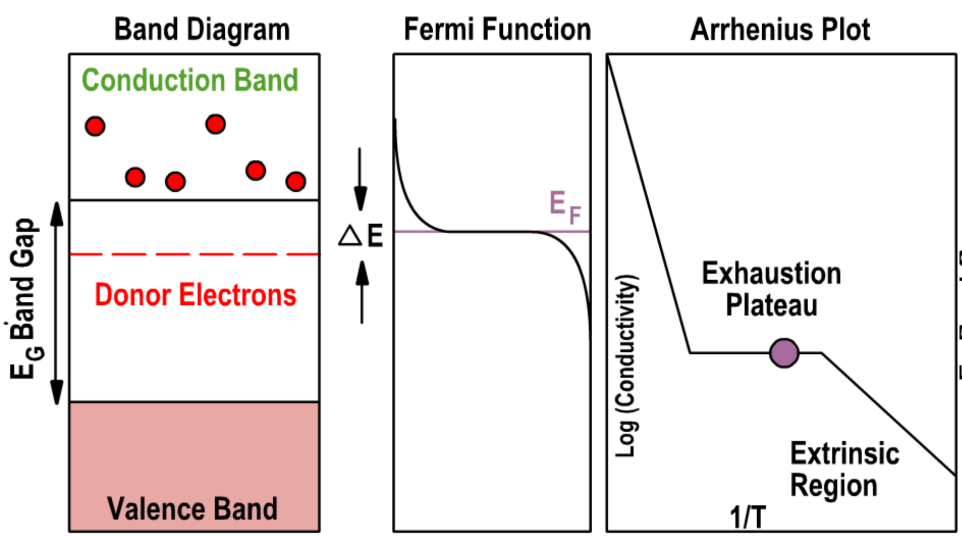
N-type Extrinsic Semiconductor



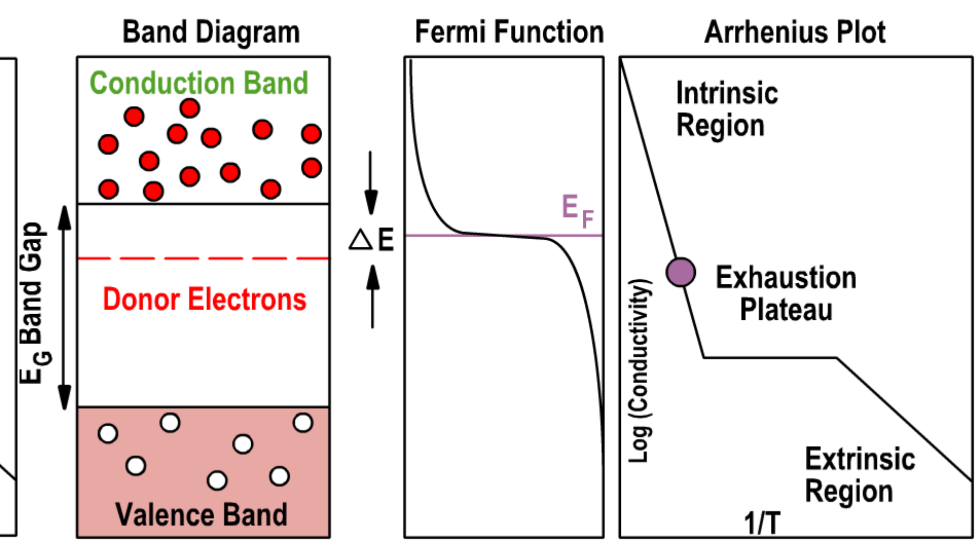
N-type Extrinsic Semiconductor



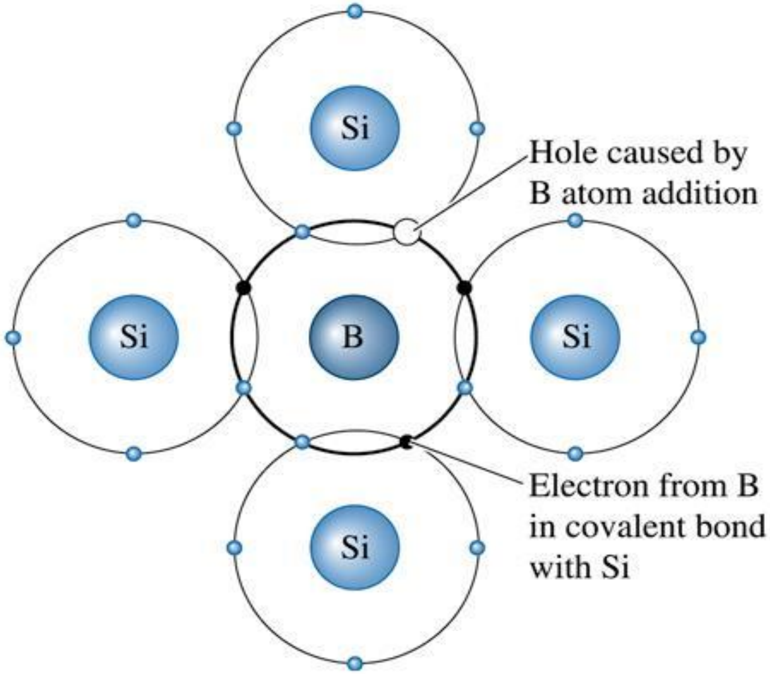
N-type Extrinsic Semiconductor

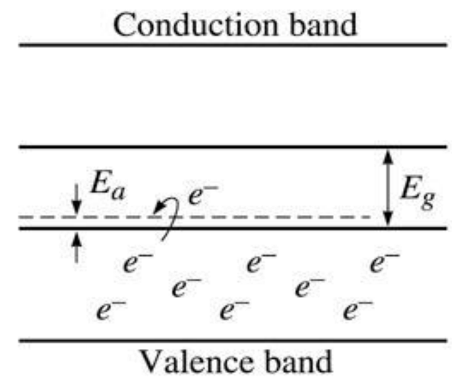


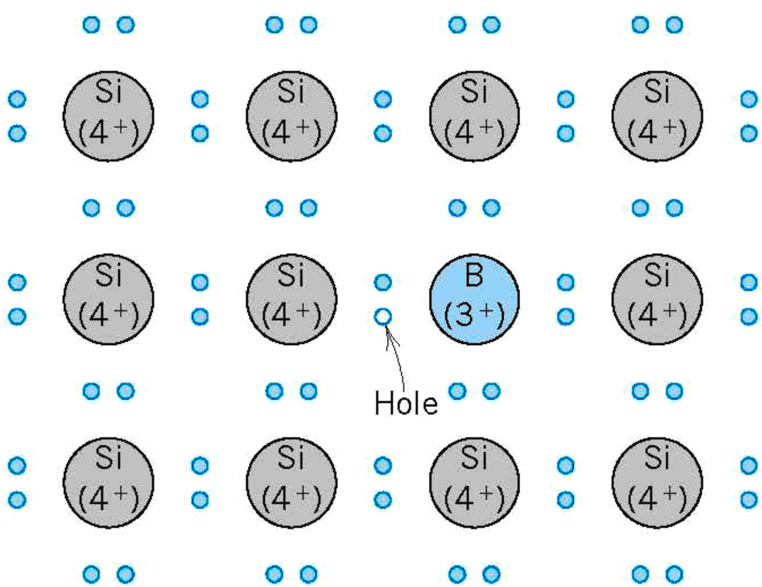
N-type Extrinsic Semiconductor

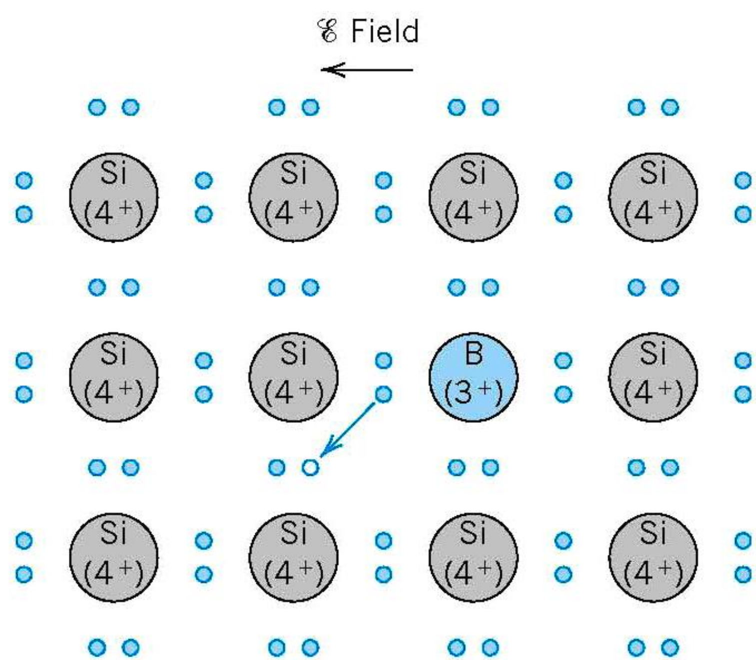


P-TYPE SEMICONDUCTOR

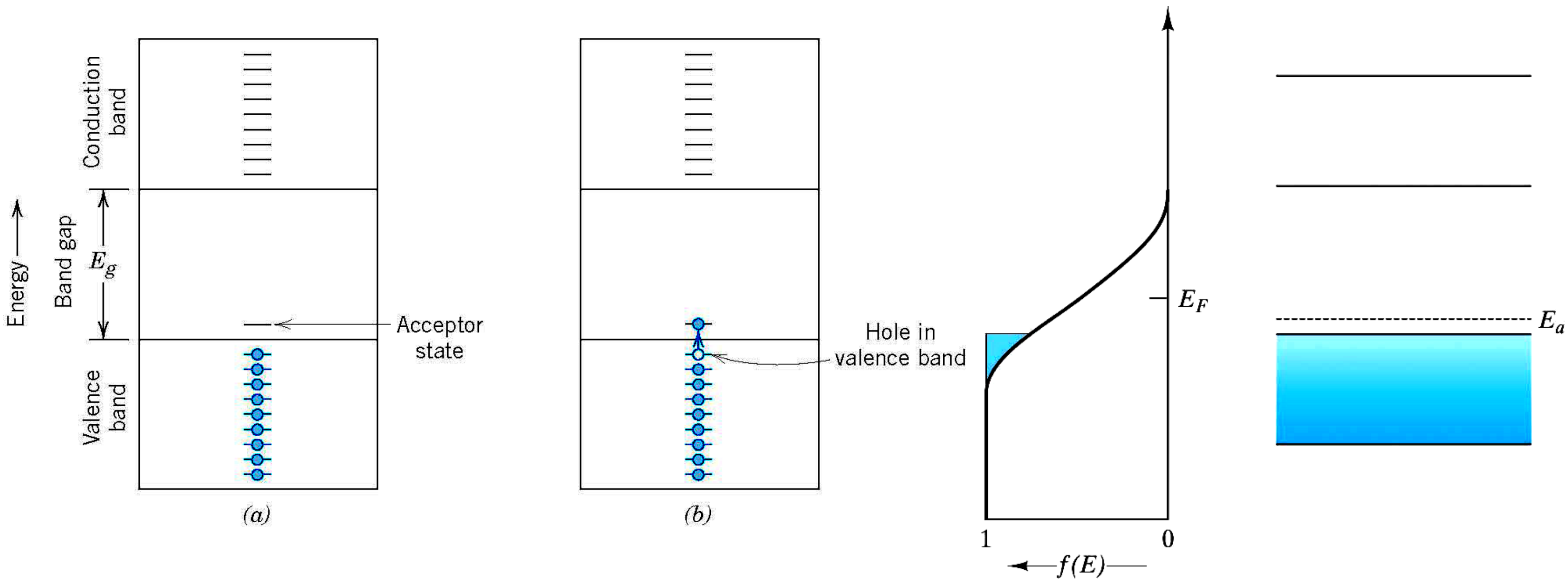




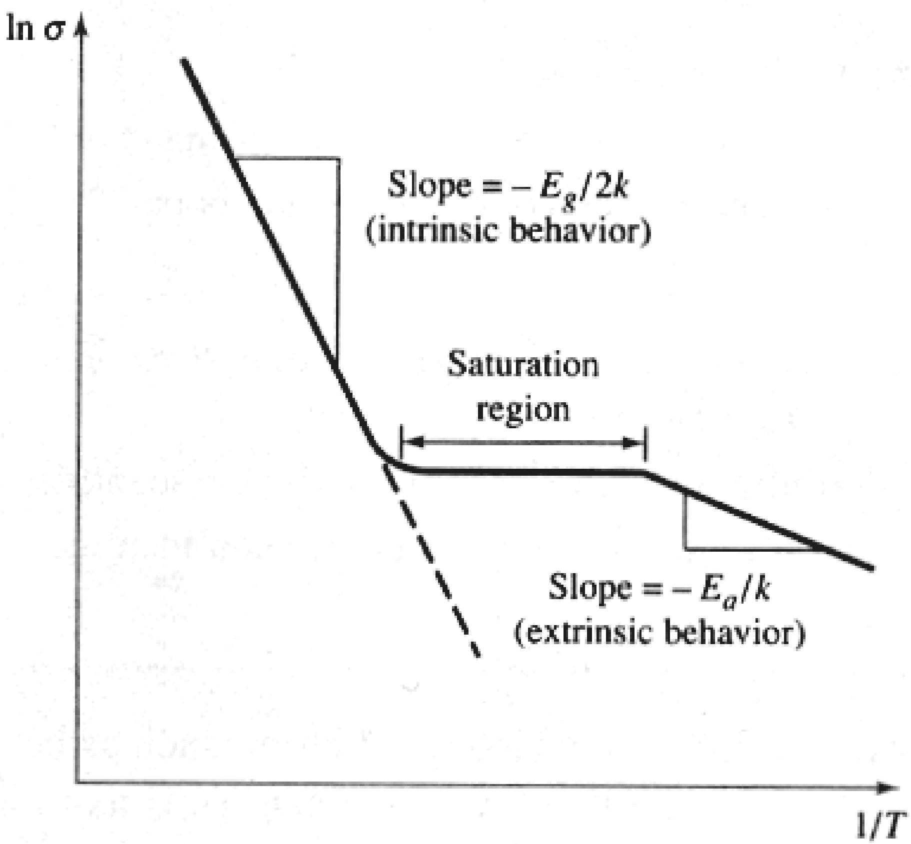




P-TYPE SEMICONDUCTOR

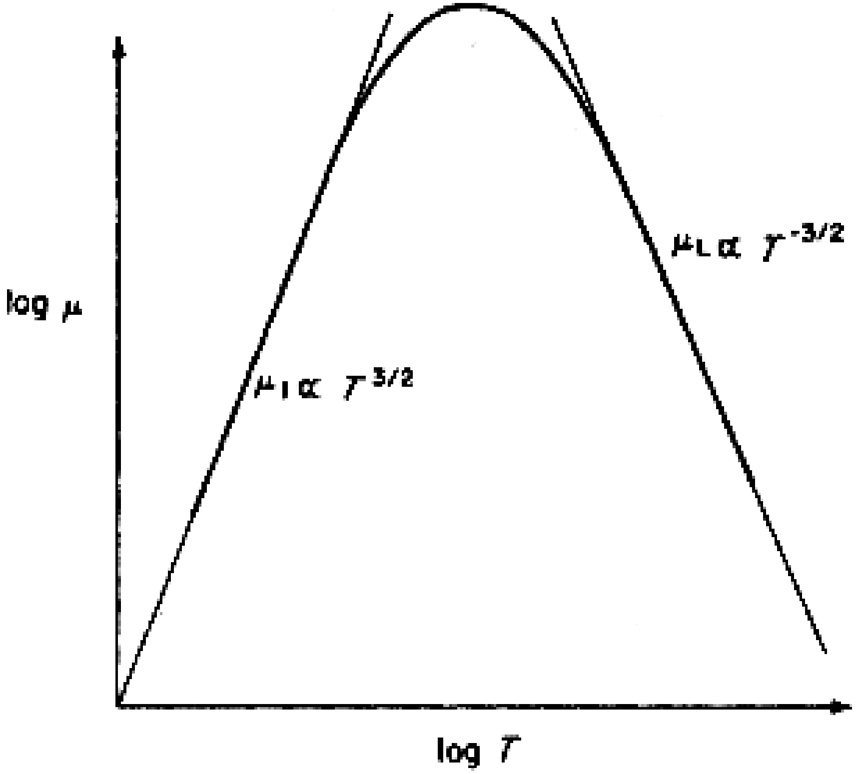


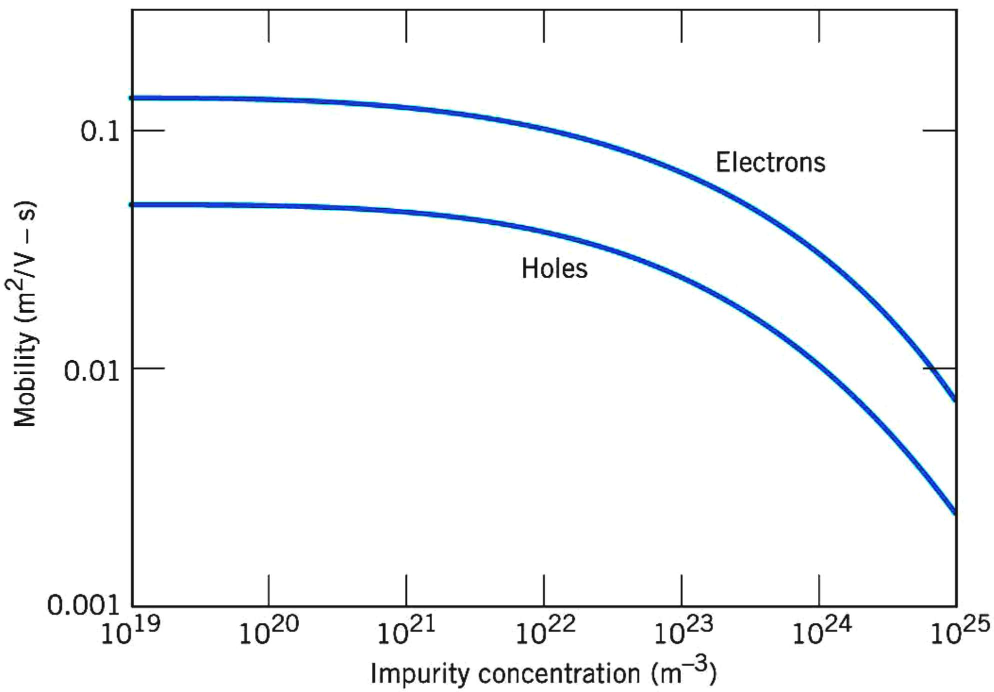
P-TYPE SEMICONDUCTOR



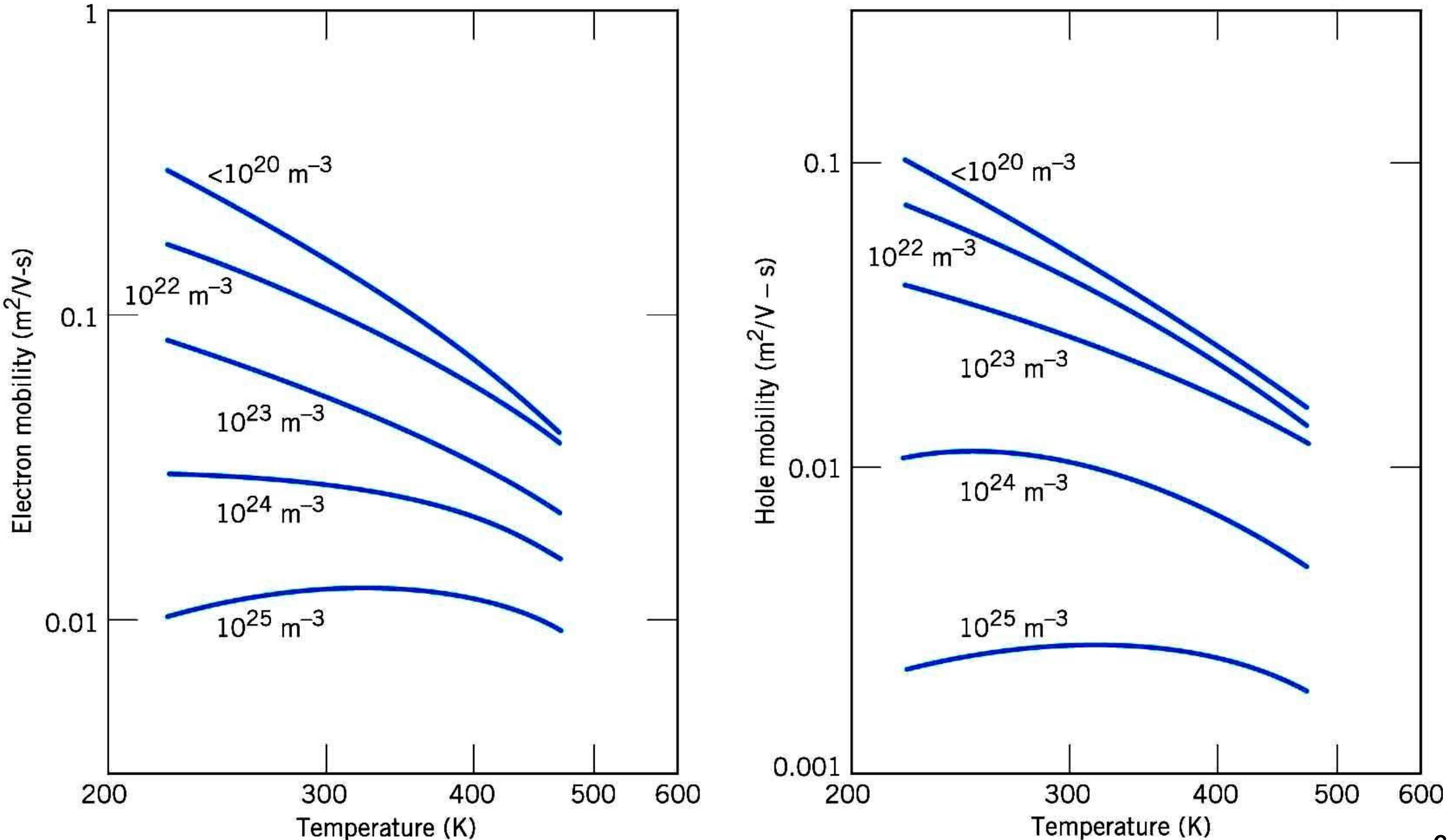
Host	Dopant	Energy level
Silicon	Sb	$E_c - E_d = 0.039$ eV
	P	$E_c - E_d = 0.044$ eV
	As	$E_c - E_d = 0.049$ eV
	Bi	$E_c - E_d = 0.069$ eV
	B	$E_a = 0.045$ eV
	Al	$E_a = 0.057$ eV
	Ga	$E_a = 0.065$ eV
	In	$E_a = 0.160$ eV
	Tl	$E_a = 0.260$ eV
Germanium	P	$E_c - E_d = 0.012$ eV
	As	$E_c - E_d = 0.013$ eV
	B	$E_a = 0.010$ eV
	Al	$E_a = 0.010$ eV

TEMPERATURE DEPENDENCE OF MOBILITY





TEMPERATURE DEPENDENCE OF MOBILITY



HALL EFFECT

- carrier density vs. carrier mobility
- Hall effect- apply electric field and magnetic field at right angle
- effect of magnetic field on free electrons

force $\vec{\mathrm{F}} = q\vec{v} \times \vec{B}$

magnstic field B_z

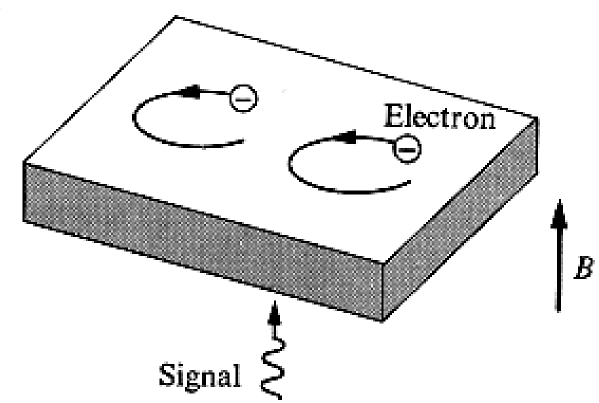
circular orbit in the *xy* plane

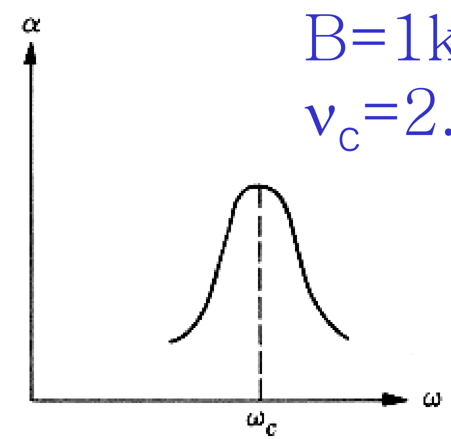
$m_e^* v^2 / r = qvB_z$

$\mathrm{w}_{\mathrm{c}} = v / r = qB_z / m_e^*$

cyclotron frequency

(effective mass)





B=1kG

ν_C=2.8GHz

laser, $w_c\tau$ □ 1, 50kG, 10K

HALL EFFECT

- carrier- drift velocity in the x-direction
- magnetic field- carrier deflected (y-direction)
- no current flow in the y direction- build up electric field
- for charge carrier-electron

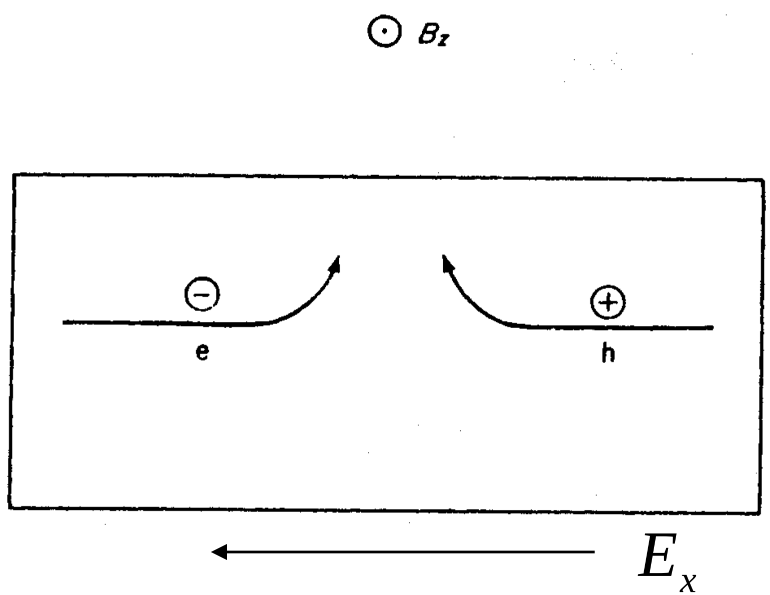
$$E = -\vec{v} \times \vec{B} = (1/nq)\,\vec{j_e} \times \vec{B}$$

$$\vec{j_e} = j_x, \quad \vec{B} = B_z$$

$$E_H = E_y = -(1/nq)\,j_x B_z$$

- for charge carrier-hole

$$E_H = E_y = (1/nq)\,j_x B_z$$



HALL EFFECT

- Hall field E_H - polarity
- $E_y = (\pm 1/nq)\, j_x B_z$
- Hall coefficient: $R_H = E_y / j_x B_z = \pm 1/nq$

  (direct measurement of carrier density)
- Hall mobility: $\mu_{\mathrm{H}} = R_H \sigma$
- example

The electrical conductivity and electron mobility for aluminum are 3.8×10^7 $(\Omega\text{-m})^{-1}$ and 0.0012 m^2/V-s, respectively. Calculate the Hall voltage for an aluminum specimen that is 15 mm thick for a current of 25 A and a magnetic field of 0.6 tesla (imposed in a direction perpendicular to the current).

HALL EFFECT

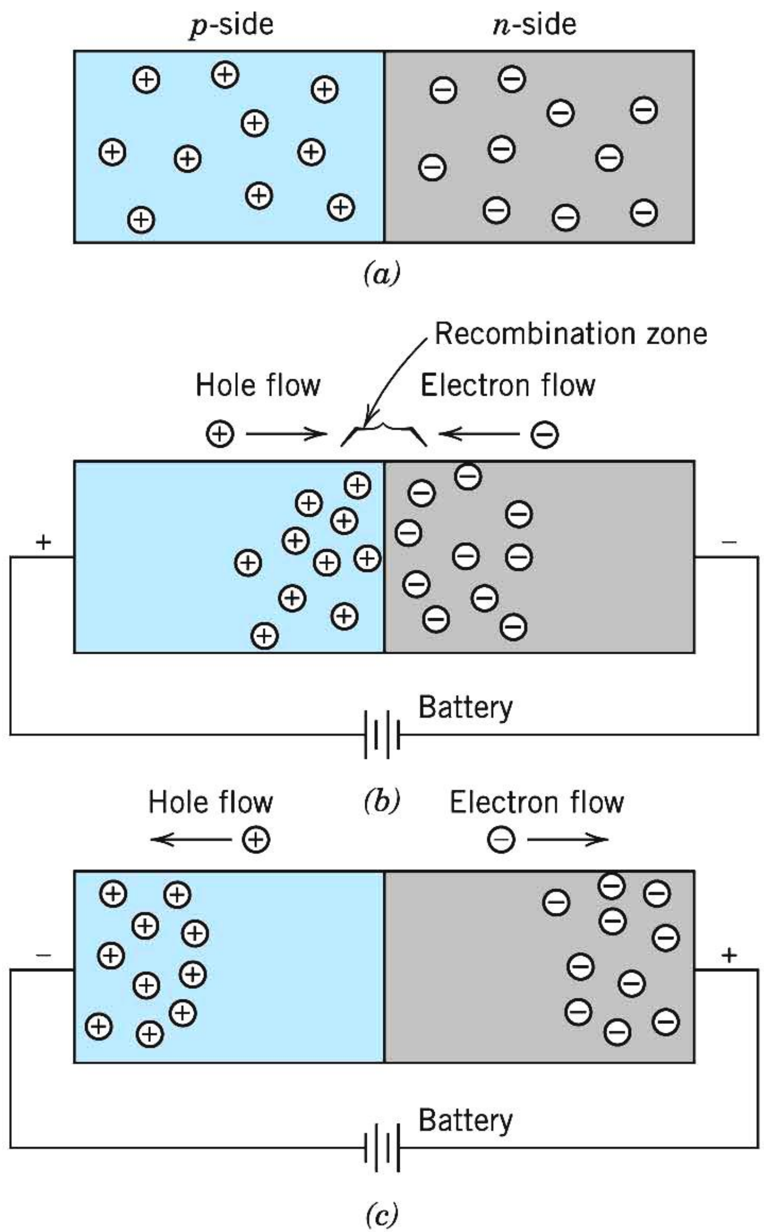
Hall Constants (in volt m^3/amp weber at Room Temperature)

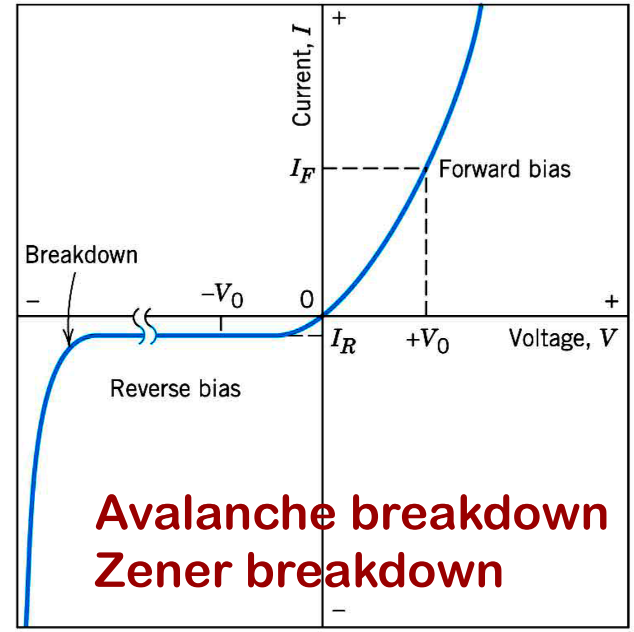
Li	Na	Cu	Ag	Au	Zn	Cd	Al
-1.7×10^{-10}	-2.50	-0.55	-0.84	-0.72	$+0.3$	$+0.6$	-0.30

- Hall coefficient when both electrons and holoes exist simutaneously

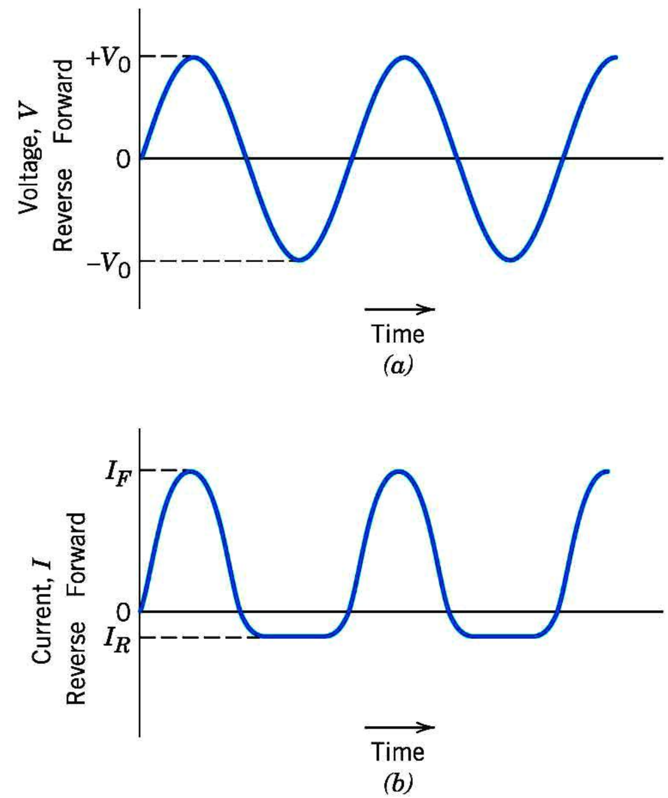
$$R = \frac{R_e\sigma_e^2 + R_h\sigma_h^2}{(\sigma_e + \sigma_h)^2}$$

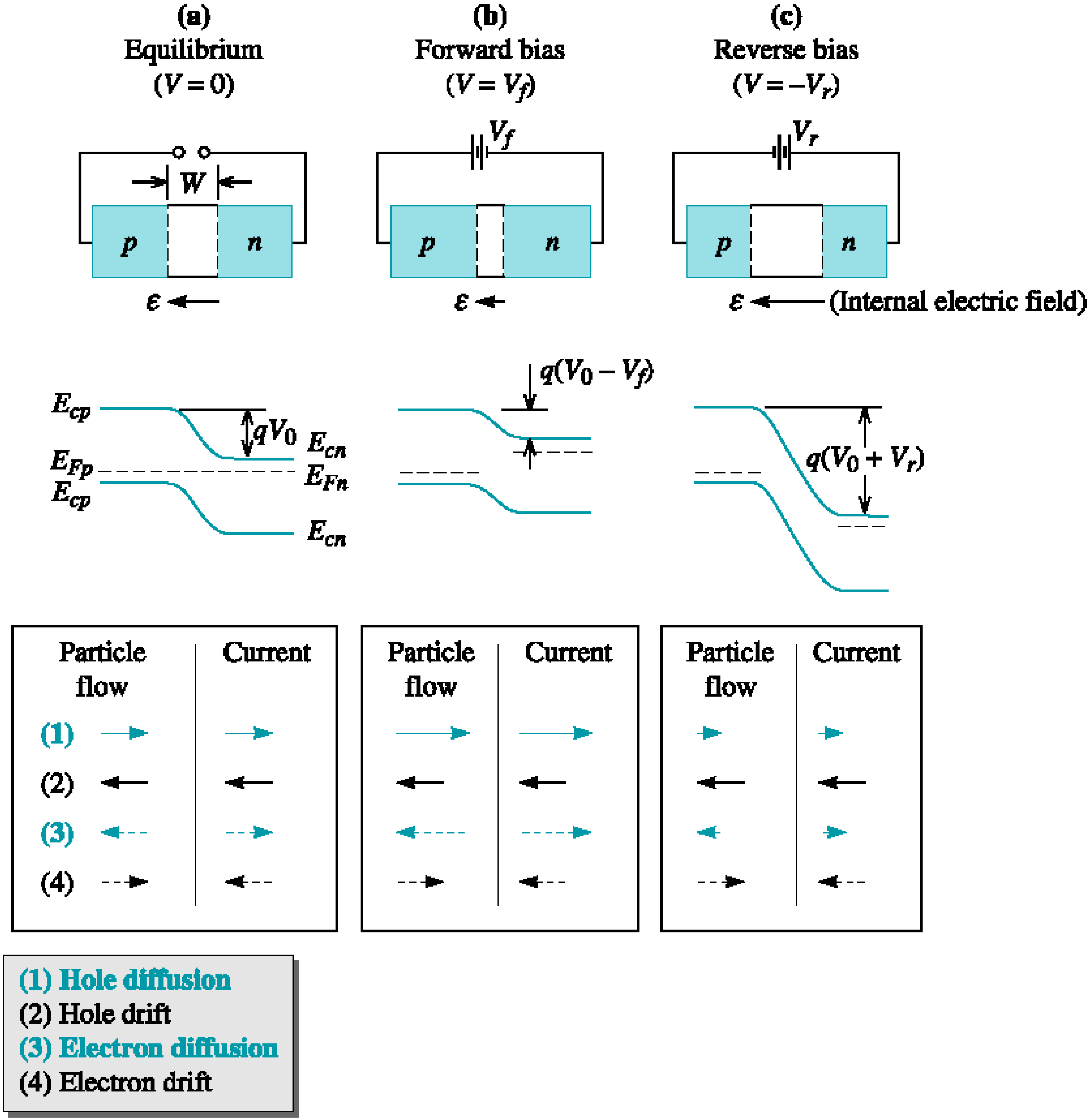
P-N JUNCTION





Avalanche breakdown
Zener breakdown





(a)
Equilibrium
(V = 0)
(b)
Forward bias
(V = Vf)
(c)
Reverse bias
(V = −Vr)
W
p
n
Vf
Vr
ε
(Internal electric field)
Ecp
EFp
Ecp
qV0
Ecn
EFn
Ecn
q(V0 − Vf)
q(V0 + Vr)
Particle flow
Current
(1)
(2)
(3)
(4)
(1) Hole diffusion
(2) Hole drift
(3) Electron diffusion
(4) Electron drift

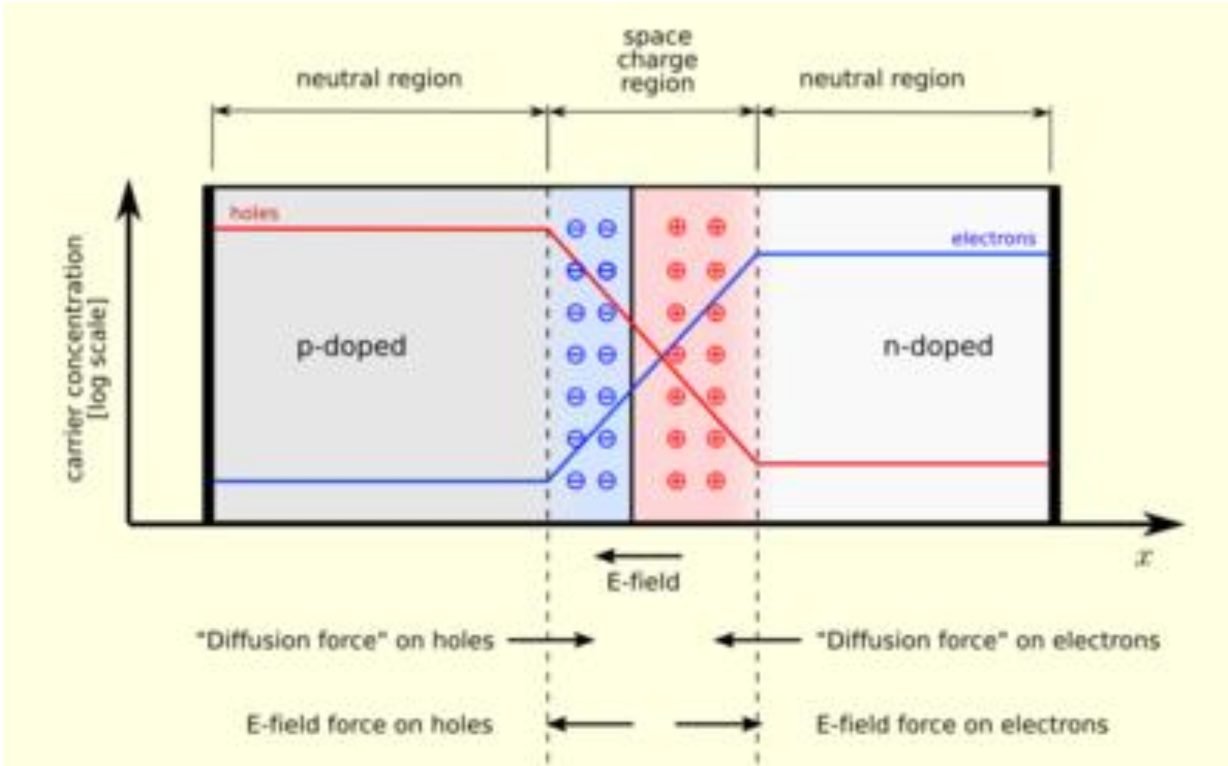


Figure A. A p–n junction in thermal equilibrium with zero-bias voltage applied. Electron and hole concentration are reported with blue and red lines, respectively. Gray regions are charge-neutral. Light-red zone is positively charged. Light-blue zone is negatively charged. The electric field is shown on the bottom, the electrostatic force on electrons and holes and the direction in which the diffusion tends to move electrons and holes. (The log concentration curves should actually be smoother with slope varying with field strength.)

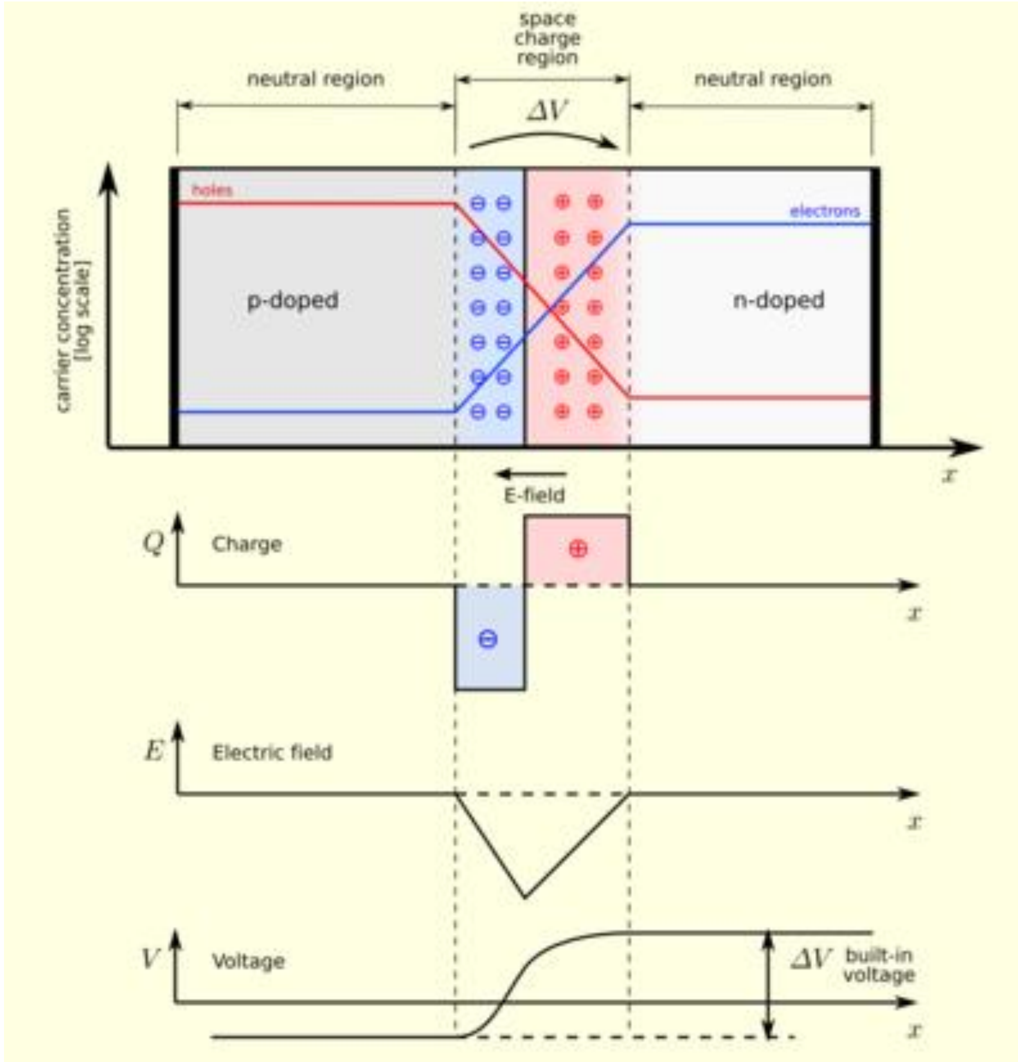
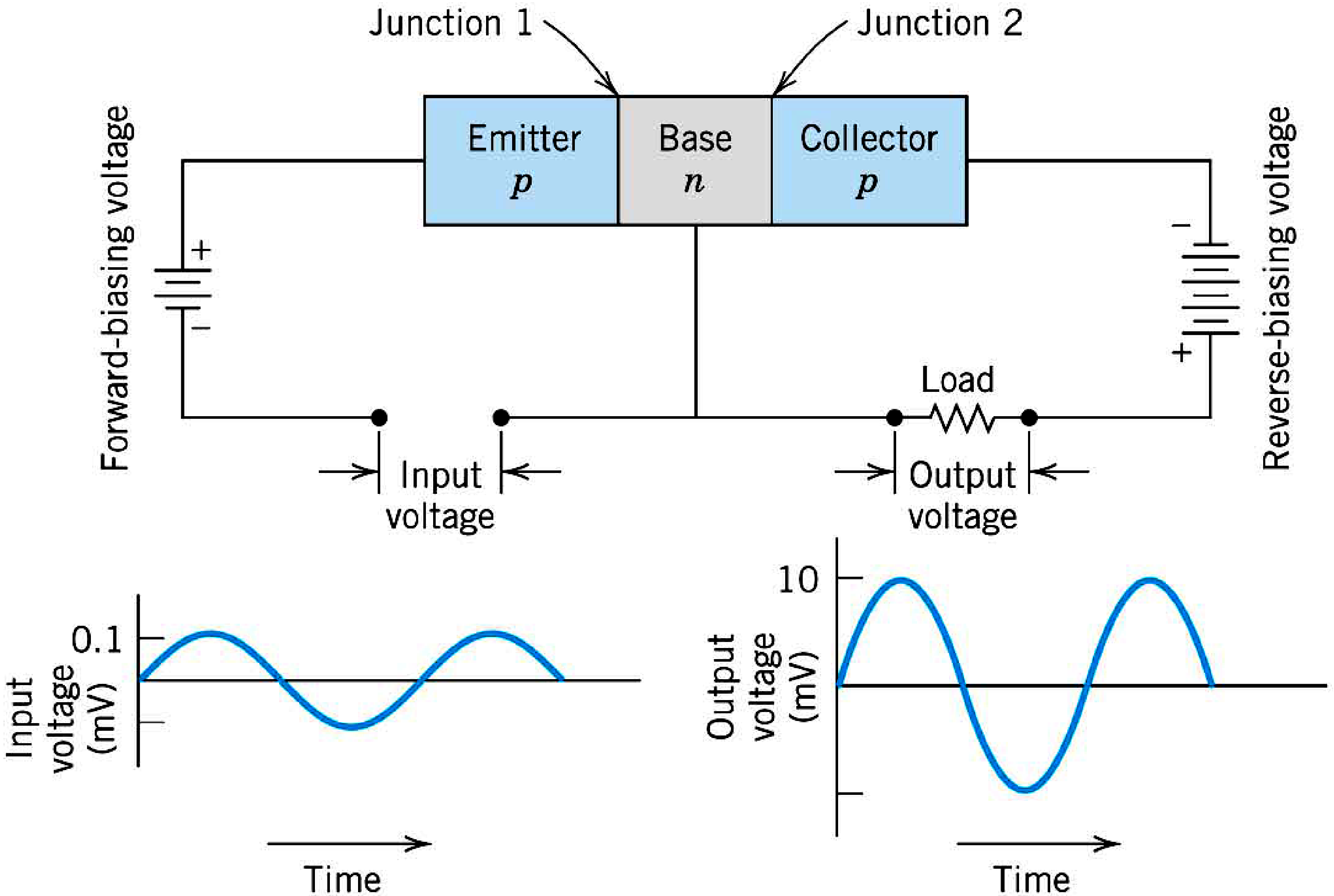


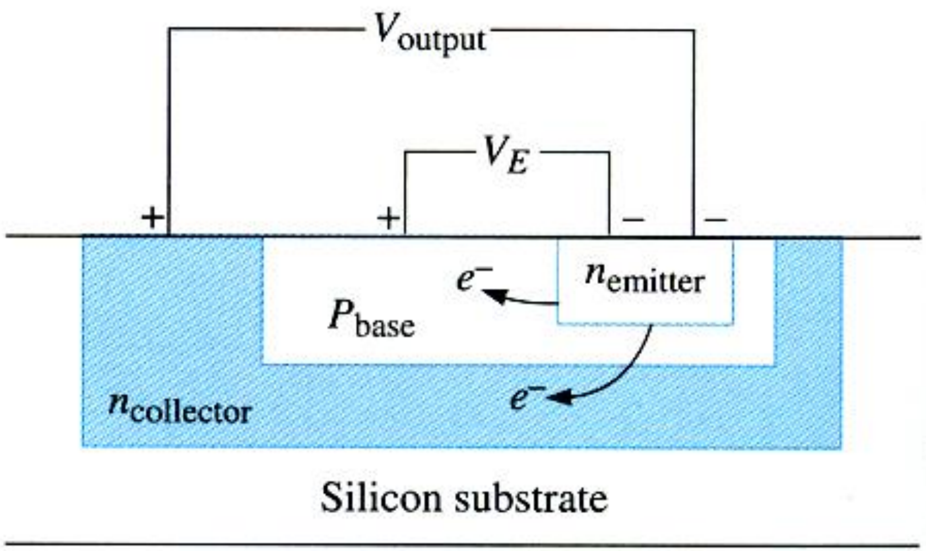
Figure B. A p–n junction in thermal equilibrium with zero-bias voltage applied. Under the junction, plots for the charge density, the electric field, and the voltage are reported. (The log concentration curves should actually be smoother, like the voltage.)

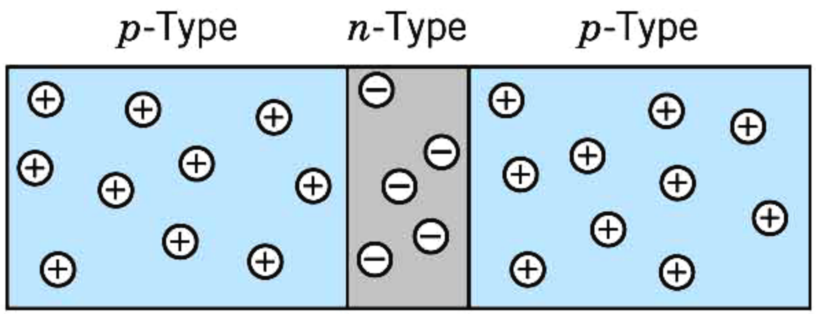
TRANSISTOR



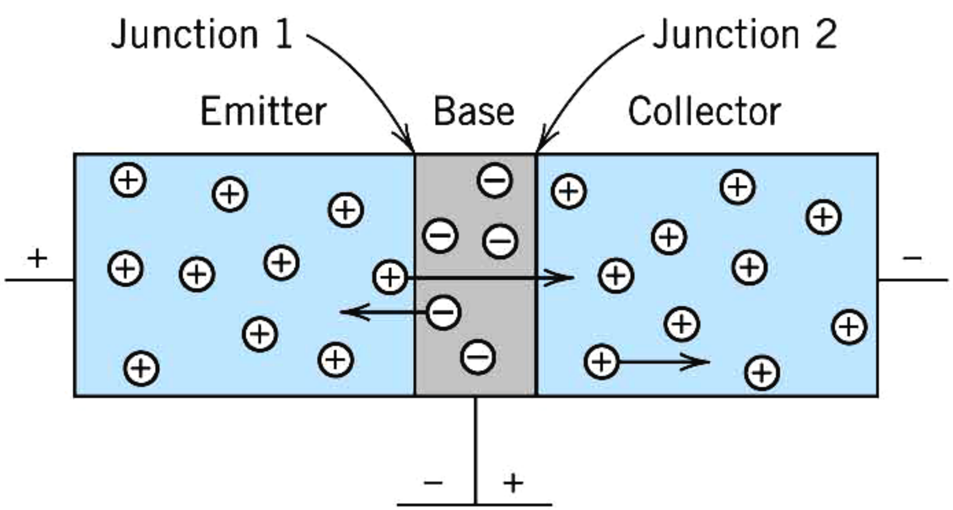
Junction 1
Junction 2
Emitter
p
Base
n
Collector
p
Forward-biasing voltage
Reverse-biasing voltage
+
−
−
+
Load
Input
voltage
Output
voltage
0.1
Input
voltage
(mV)
Time
10
Output
voltage
(mV)
Time

TRANSISTOR





(a)



(b)