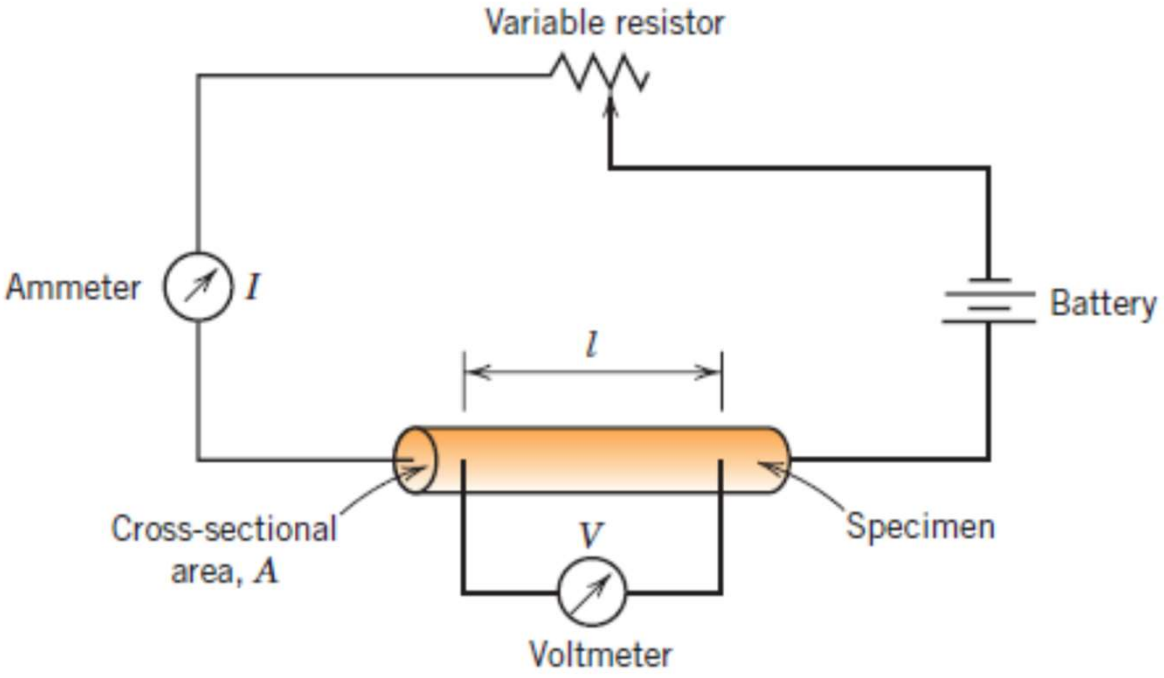
Electrical and Electronic Properties

OHM's Law

$$V = IR$$

$$R \propto \frac{l}{A} \Rightarrow R = \rho \frac{l}{A}$$

The unit of resistivity ρ is ohm-meter (Ω·m)



Electrical Conductivity

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

An equivalent statement of Ohm's law:

$$J = \sigma E,$$

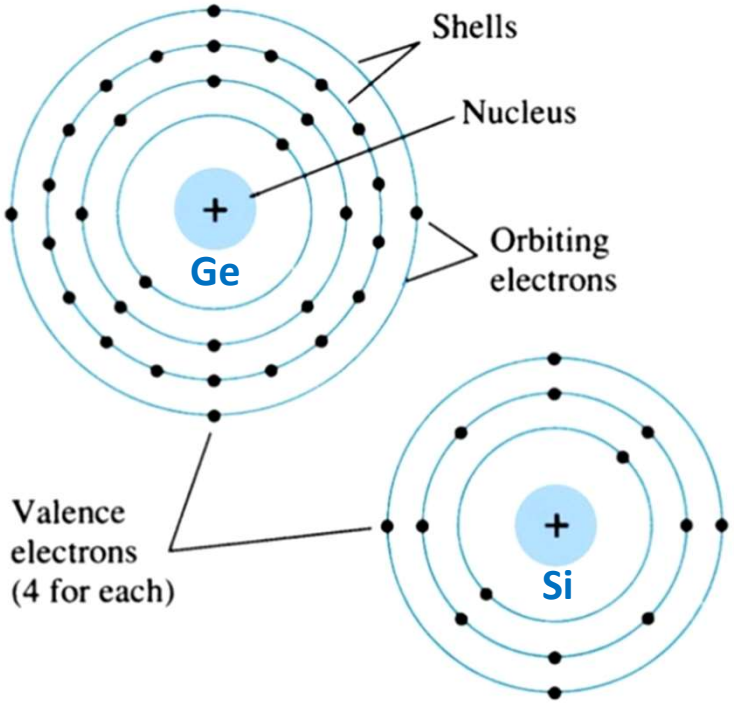
Where, J is the current density;
E is the electric field intensity (Voltage difference per unit length)

Classification of materials based on conductivities:

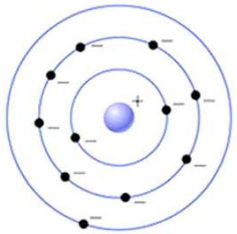
- **Metals** are good conductors, having conductivities on the order of 10^{7} $(\Omega \cdot m)^{-1}$.
- **Insulators** having very low conductivities of 10^{-10} and 10^{-20} $(\Omega \cdot m)^{-1}$.
- **Semiconductors** having conductivities, from 10^{-6} to 10^{4} $(\Omega \cdot m)^{-1}$.

Bohr model

- ✓ **Bohr model of the atom:** An atom is composed of a **nucleus** - *protons, neutrons & electrons*
- ✓ The electrons are distribute themselves in shells ***(Quantized energy levels).***
- ✓ Electrons in the outermost shell/orbit are called as **valence electrons**.



The Atom



- ✓ In case of **Si** atom:

  Atomic no: **Z= 14**

  Electronic configuration:

$$1S^2\ 2S^2 2P^6\ 3S^2 3P^2$$

Inner Orbit

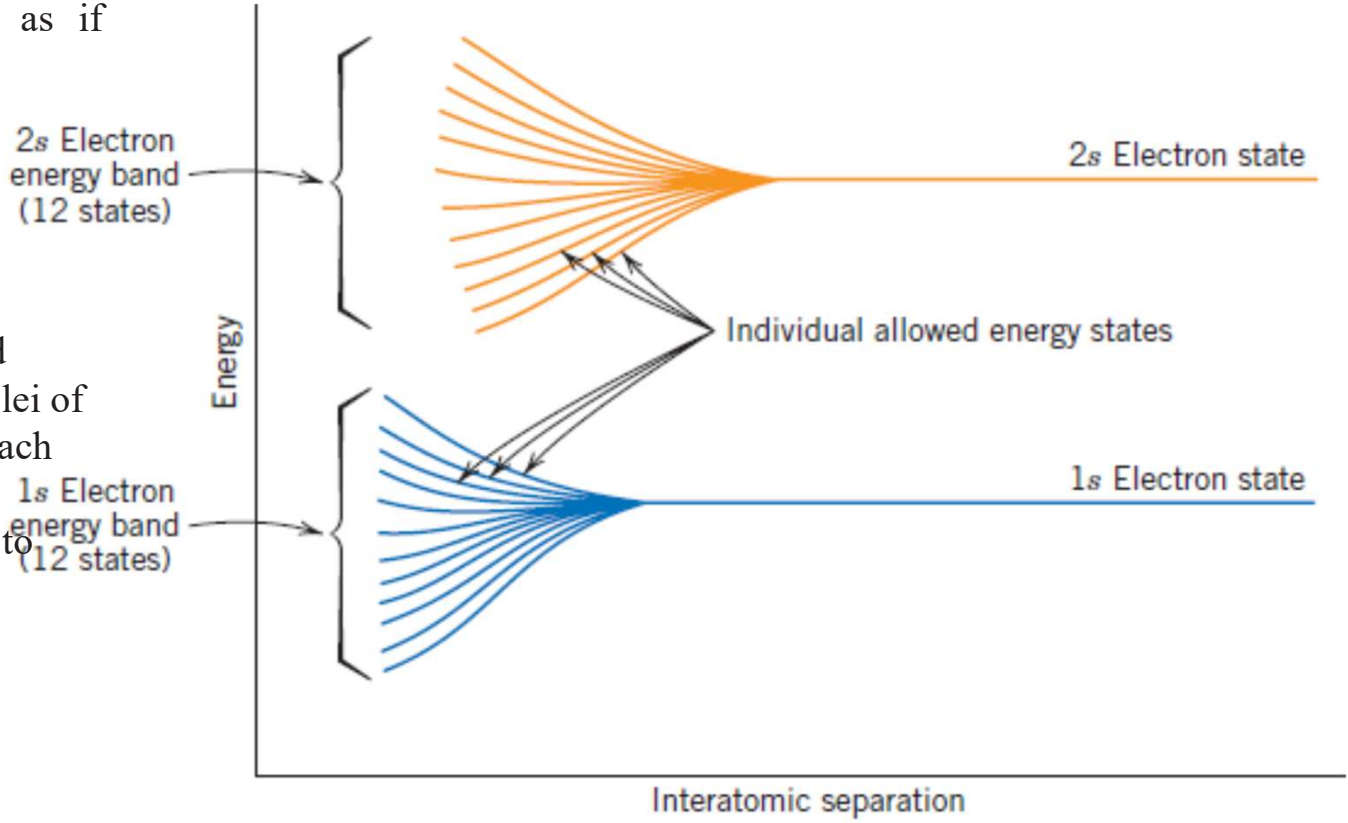
Outer Orbit/ Valance e^-

Electronic and Ionic Conduction

At relatively large separation distances, each atom is independent of all the others and has the atomic energy levels and electron configuration as if isolated.

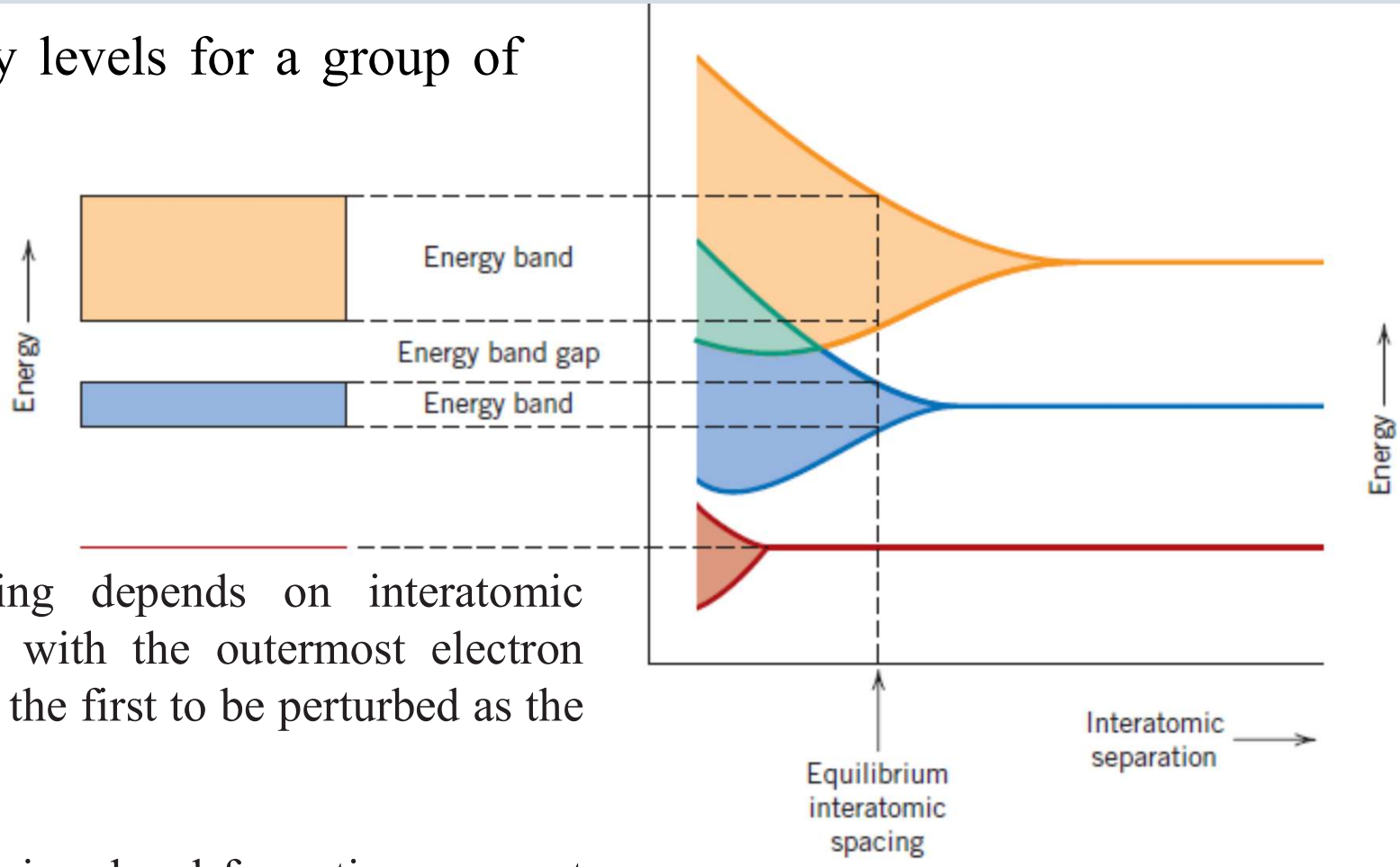
However, as the atoms come within close proximity of one another, electrons are acted upon, or *perturbed,* by the electrons and nuclei of adjacent atoms. This influence is such that each distinct atomic state may split into a series of closely spaced electron states in the solid to form what is termed an **electron energy band.**

Energy levels for a group of 12 atoms.



Electronic and Ionic Conduction

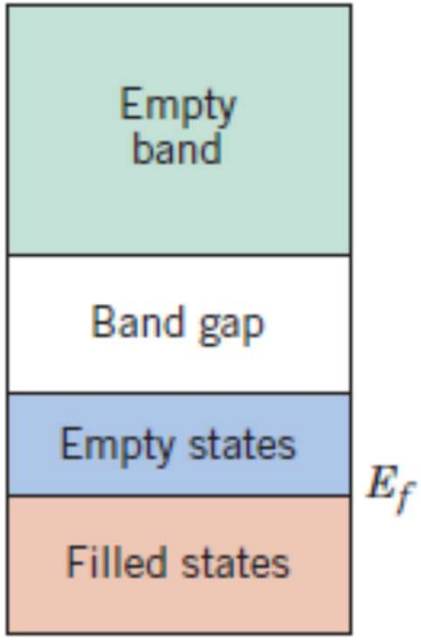
Energy levels for a group of atoms.



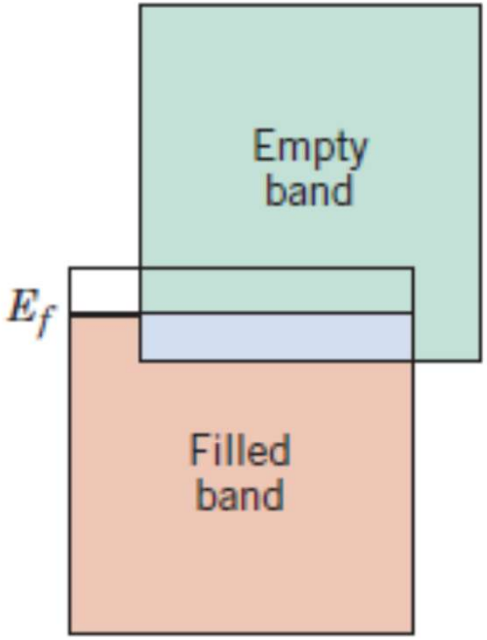
The extent of splitting depends on interatomic separation and begins with the outermost electron shells because they are the first to be perturbed as the atoms coalesce.

At the equilibrium spacing, band formation may not occur for the electron subshells nearest the nucleus,

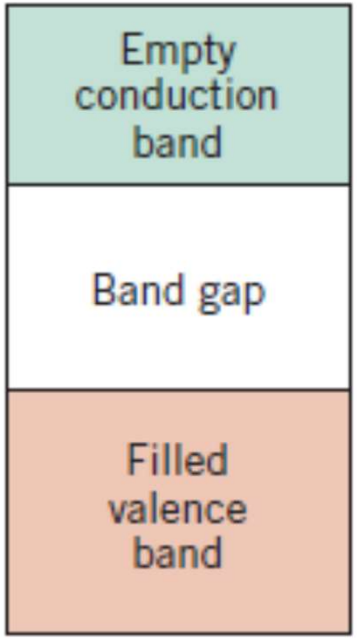
Electronic and Ionic Conduction



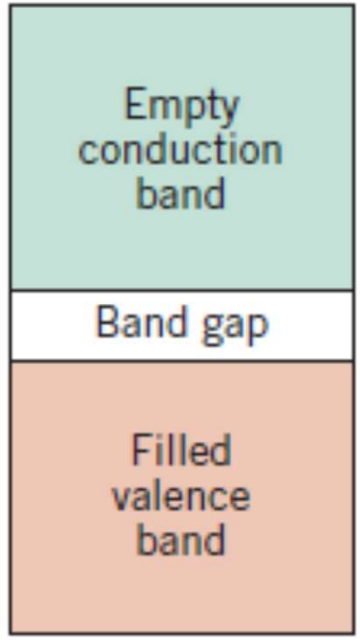
Example: Copper



Example: Magnesium



Example: Insulators

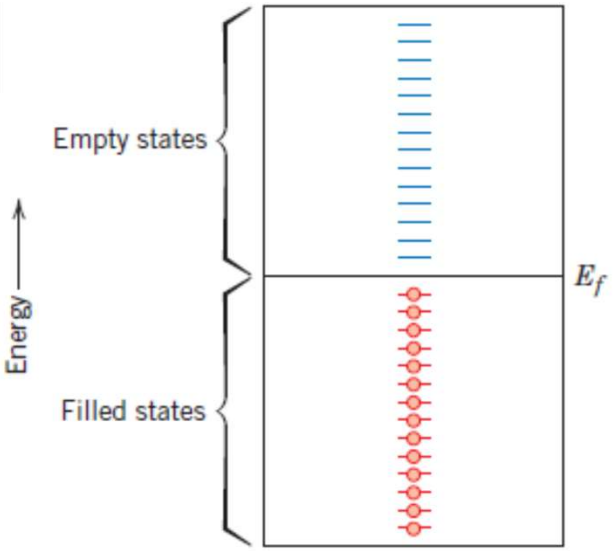


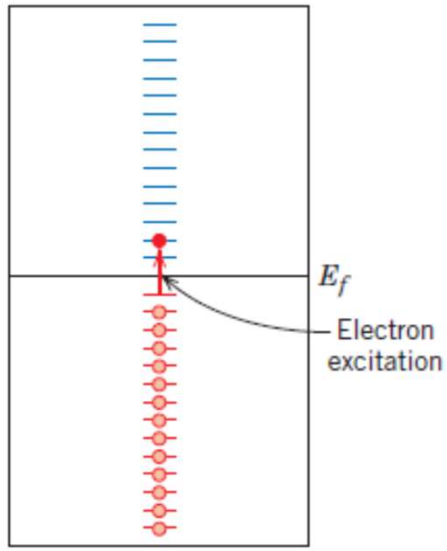
Example: Semiconductors

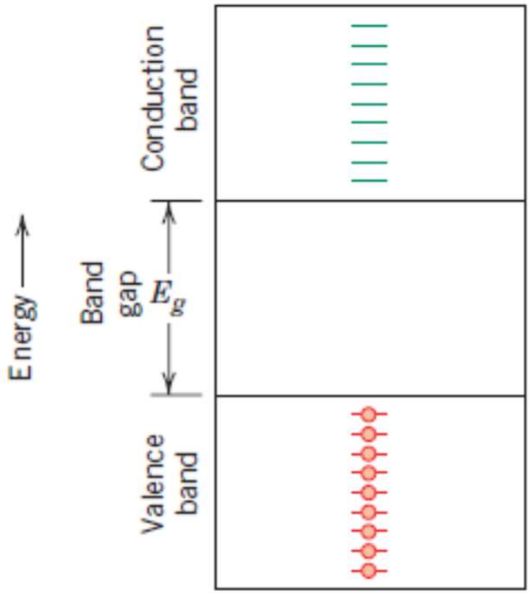
- **Fermi energy (E_f):** The energy corresponding to the highest filled state at 0 K.

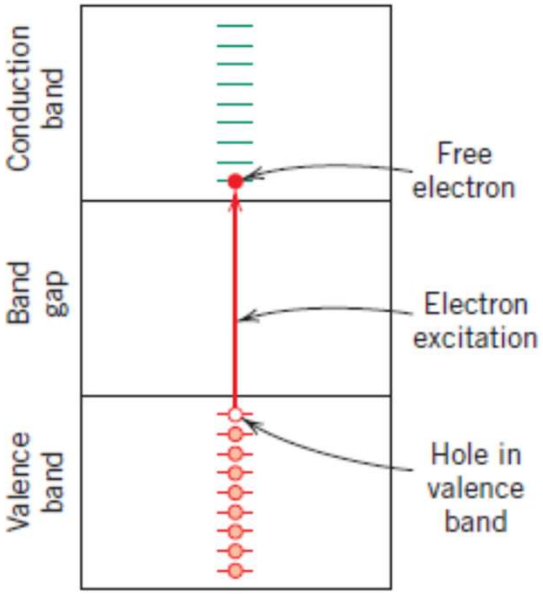
Electronic and Ionic Conduction

Generally in metals, the energy provided by an electric field is sufficient to excite large numbers of electrons into these conducting states.









For insulator or semiconductor,
For many materials, this band gap is several electron volts wide. Most often the excitation energy is from a nonelectrical source such as heat or light, usually the former.

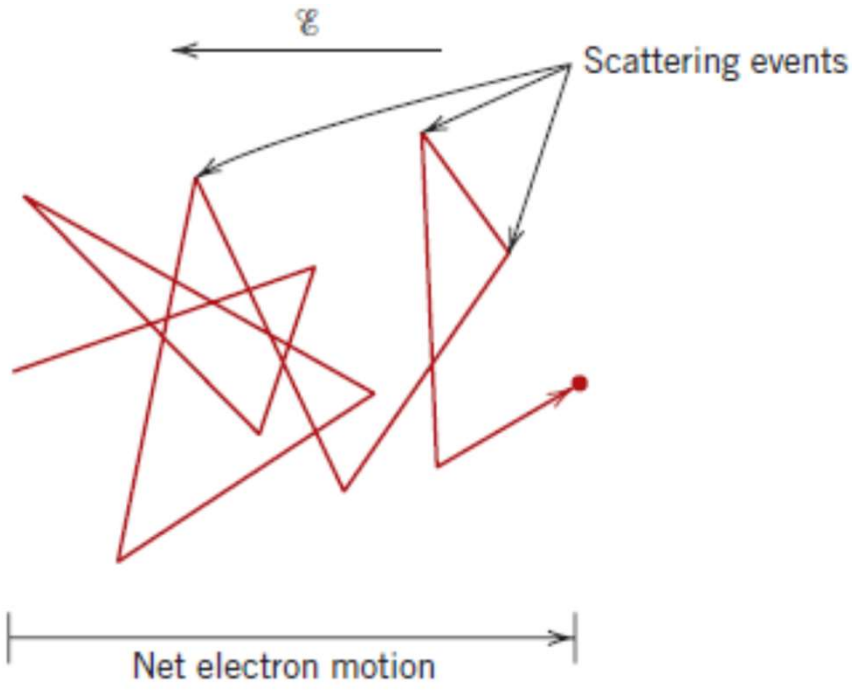
Electron mobility in a crystal

When an electric field is applied, all electrons experience an acceleration in a direction opposite to that of the field, by virtue of their negative charge. According to quantum mechanics, there is no interaction between an accelerating electron and atoms in a perfect crystal lattice.

Under such circumstances, all the free electrons should accelerate as long as the electric field is applied, which would give rise to an electric current that is continuously increasing with time.

However, we know that a current reaches a constant value the instant that a field is applied,

indicating that there exist what might be termed *frictional forces.*



Electron mobility in a crystal

- Frictional forces result from the scattering of electrons by imperfections in the crystal lattice, including impurity atoms, vacancies, interstitial atoms, dislocations, and even the thermal vibrations of the atoms themselves.

- An electron loses its kinetic energy as it moves across due to an external excitation source.
- Drift velocity is used to describe the average electron velocity:

$$v_d = \mu_e E$$

- μ_e is called the electron mobility.
- Conductivity $\sigma = n|e|\mu_e$, where n is the number of free or conducting electrons per unit volume and $|e| = 1.6\text{X}10^{-1}$ C

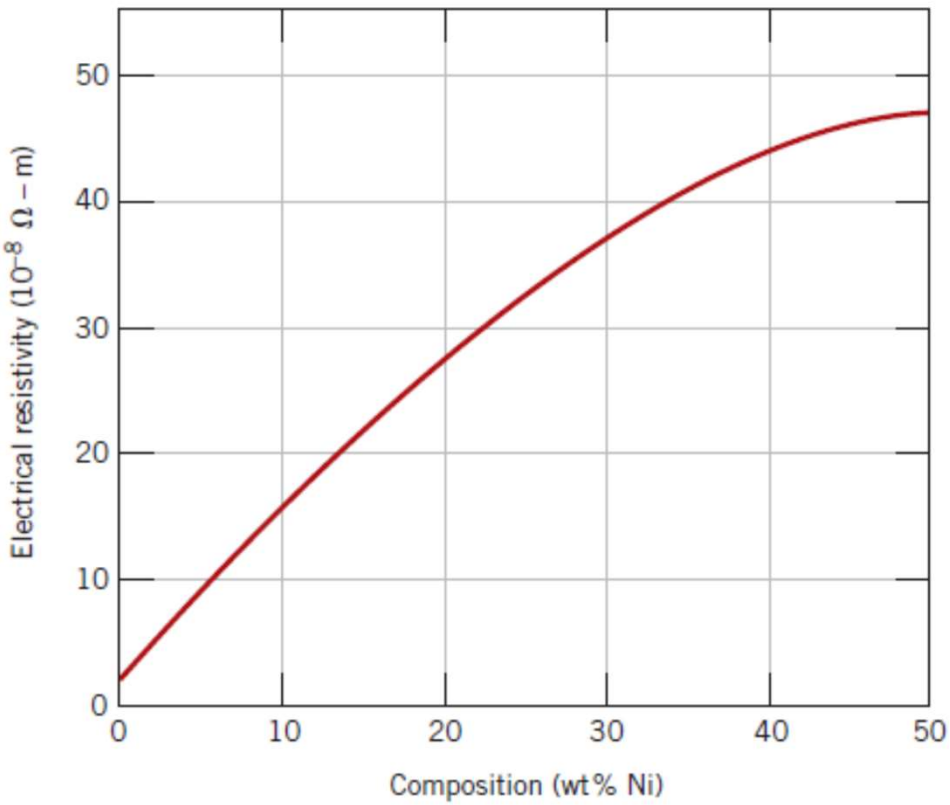
Electrical Resistivity of Metals

Matthiessen's rule: overall resistivity of a metal is sum of the contributions from each of the factors – thermal, impurities and plastic deformation.

$$\rho_{\text{total}} = \rho_t + \rho_i + \rho_d$$

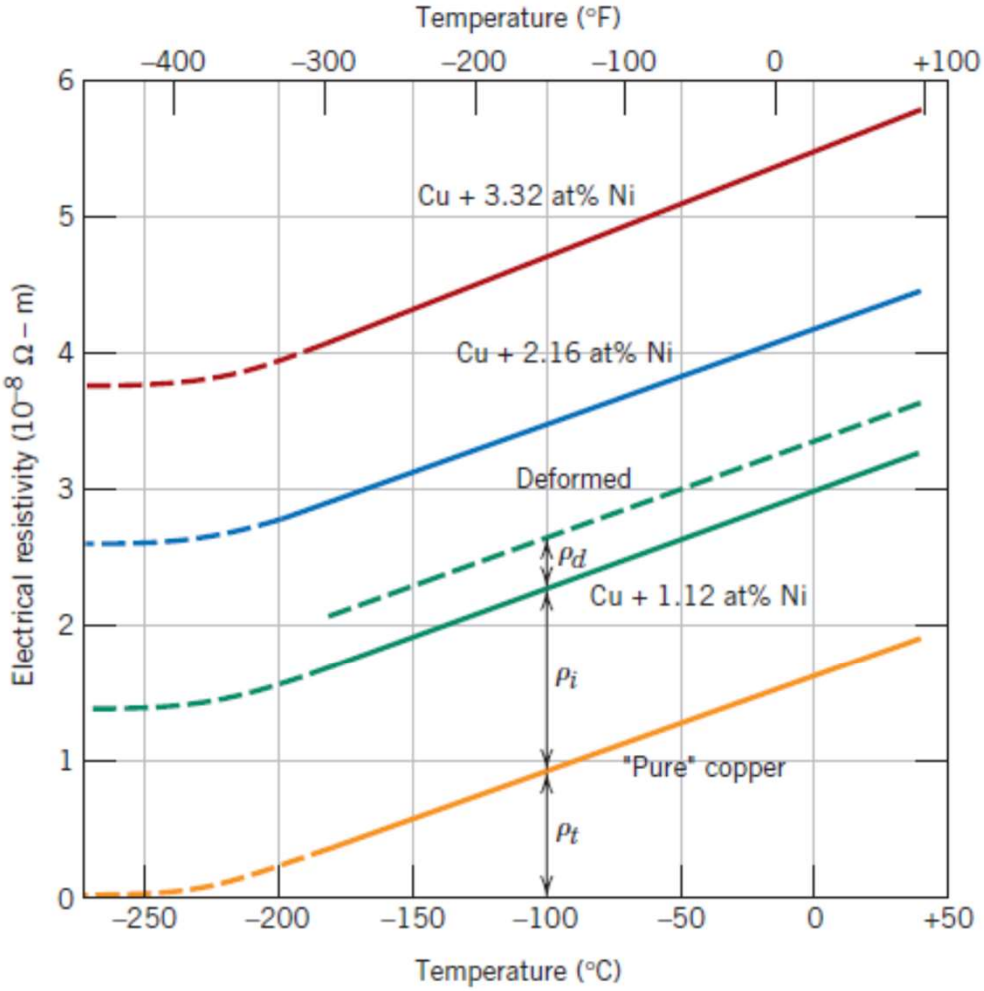
$$\rho_t = \rho_0 + aT$$

$$\rho_i = \rho_\alpha V_\alpha + \rho_\beta V_\beta$$



Electrical Resistivity of Metals

Metal	*Electrical Conductivity* $[(\Omega\text{-}m)^{-1}]$
Silver	6.8×10^7
Copper	6.0×10^7
Gold	4.3×10^7
Aluminum	3.8×10^7
Brass (70Cu–30Zn)	1.6×10^7
Iron	1.0×10^7
Platinum	0.94×10^7
Plain carbon steel	0.6×10^7
Stainless steel	0.2×10^7

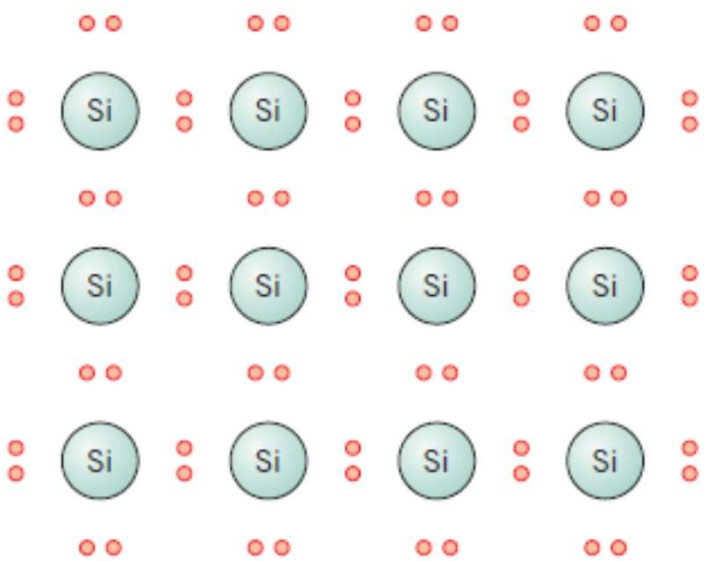


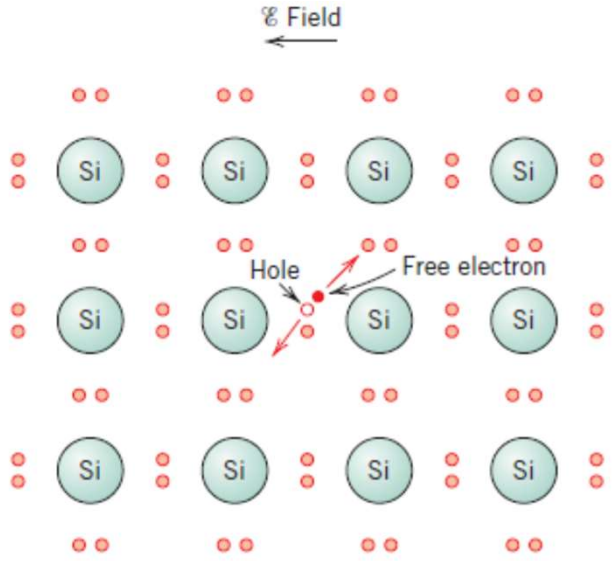
Semiconductivity

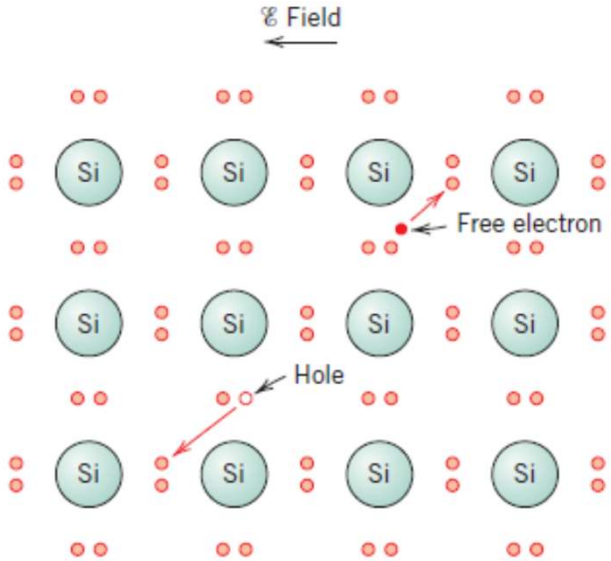
Intrinsic Semiconductors: Band gap < 2ev.
Examples: Si, Ge, GaAs, InSb

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 Conductivity







Intrinsic Conductivity

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

$$n = p = n_i$$

n_i is the charge carrier concentration

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

Computation of the Room-Temperature Intrinsic Carrier Concentration for Gallium Arsenide

For intrinsic gallium arsenide, the room-temperature electrical conductivity is $3 \times 10^{-7}\,(\Omega\cdot\text{m})^{-1}$; the electron and hole mobilities are, respectively, 0.80 and 0.04 $\text{m}^2/\text{V}\cdot\text{s}$. Compute the intrinsic carrier concentration n_i at room temperature.

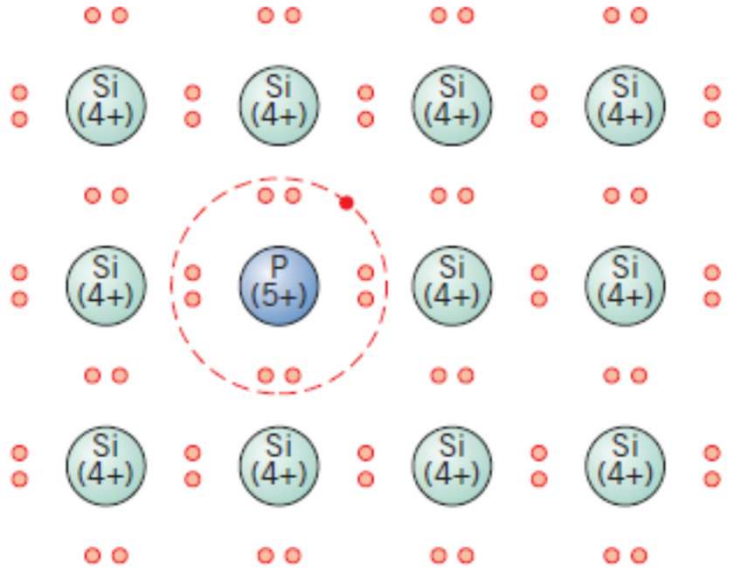
$$n_i = \frac{\sigma}{|e|(\mu_e + \mu_h)}$$

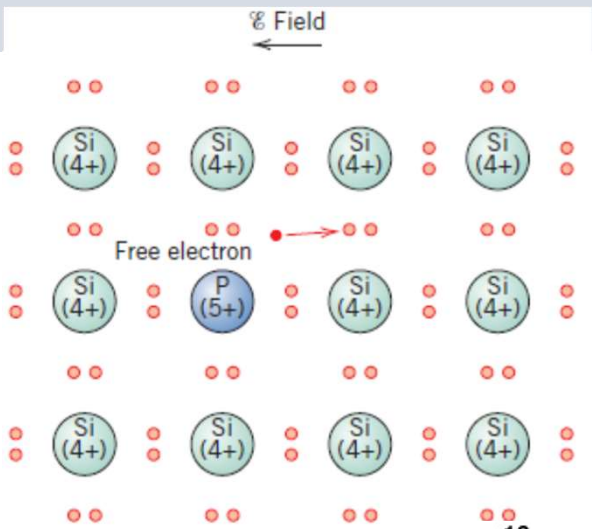
$$= \frac{3 \times 10^{-7}\,(\Omega\cdot\text{m})^{-1}}{(1.6 \times 10^{-19}\,\text{C})[(0.80 + 0.04)\,\text{m}^2/\text{V}\cdot\text{s}]}$$

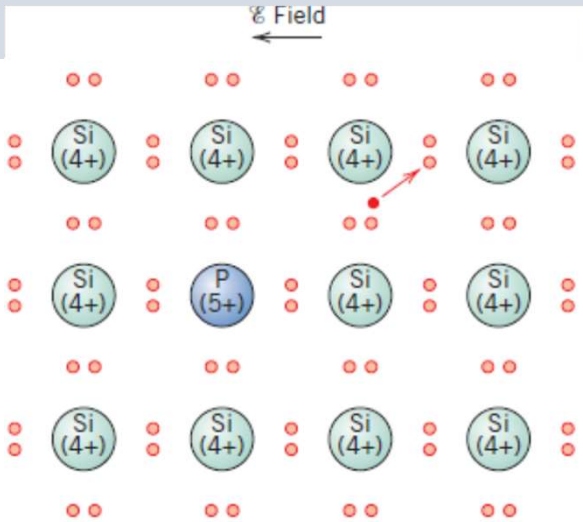
$$= 2.2 \times 10^{12}\,\text{m}^{-3}$$

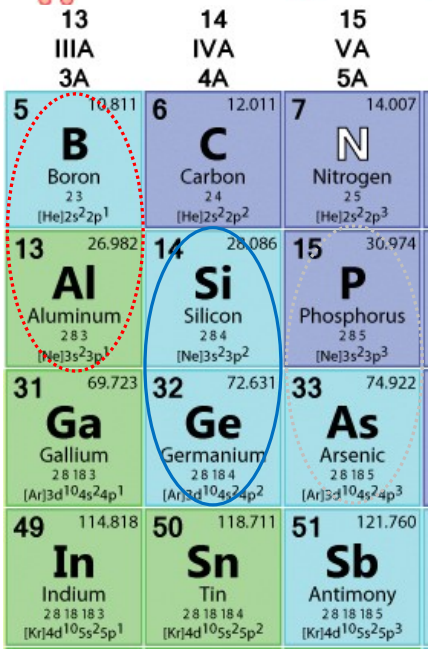
Extrinsic Semiconductors

n – type extrinsic semiconductor









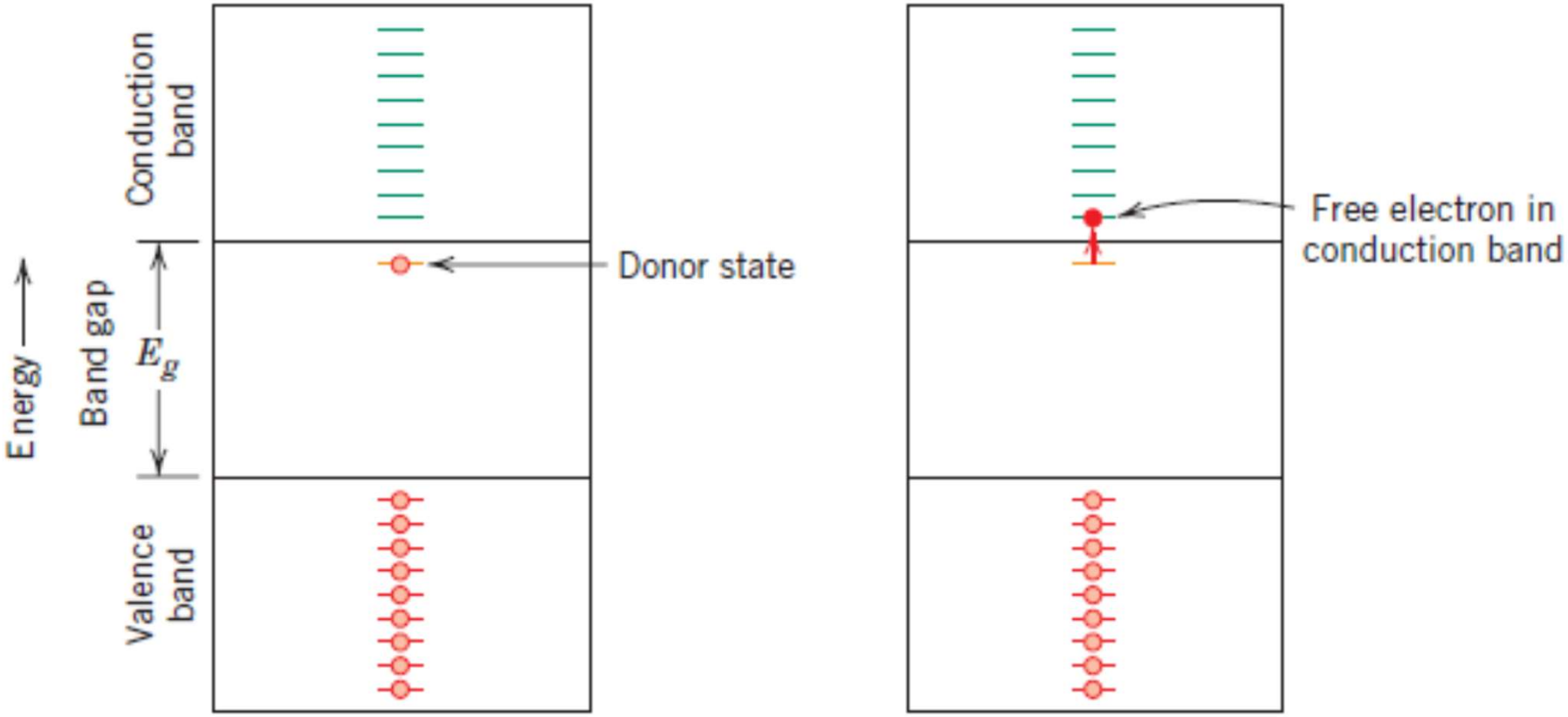
- The conductivity in an *n-type* extrinsic semiconductor is

$$\sigma \cong n|e|\mu_e$$

Here, μ_e: Electron mobility

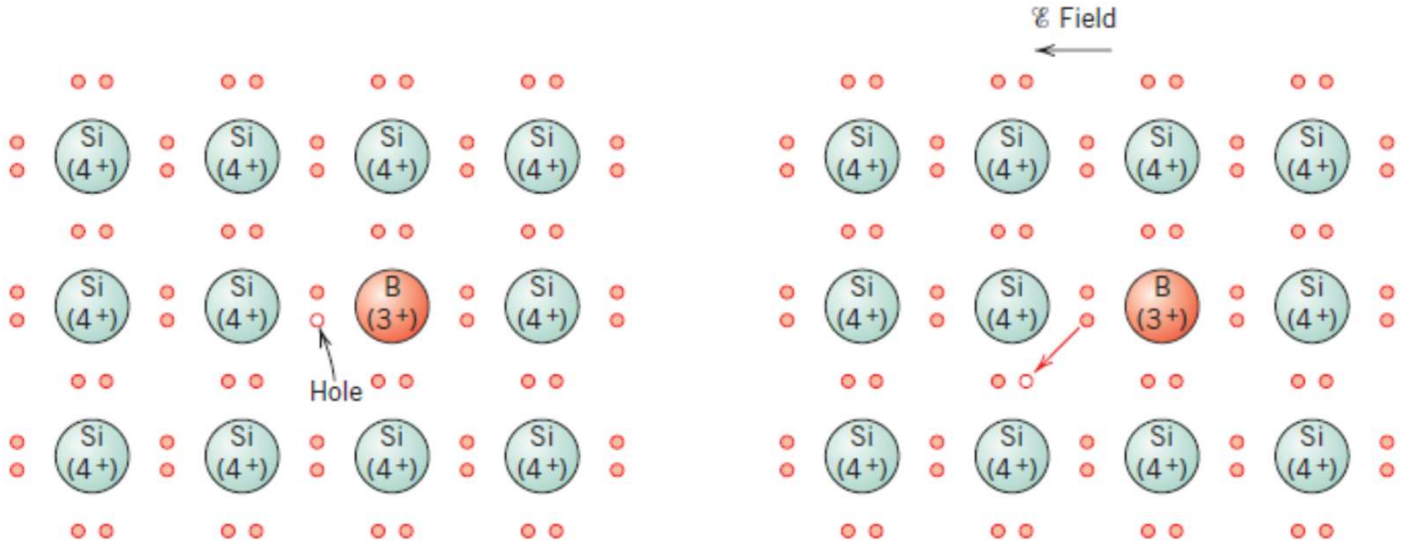
Extrinsic Semiconductors

n – type extrinsic semiconductor



Extrinsic Semiconductors

p–type extrinsic semiconductor



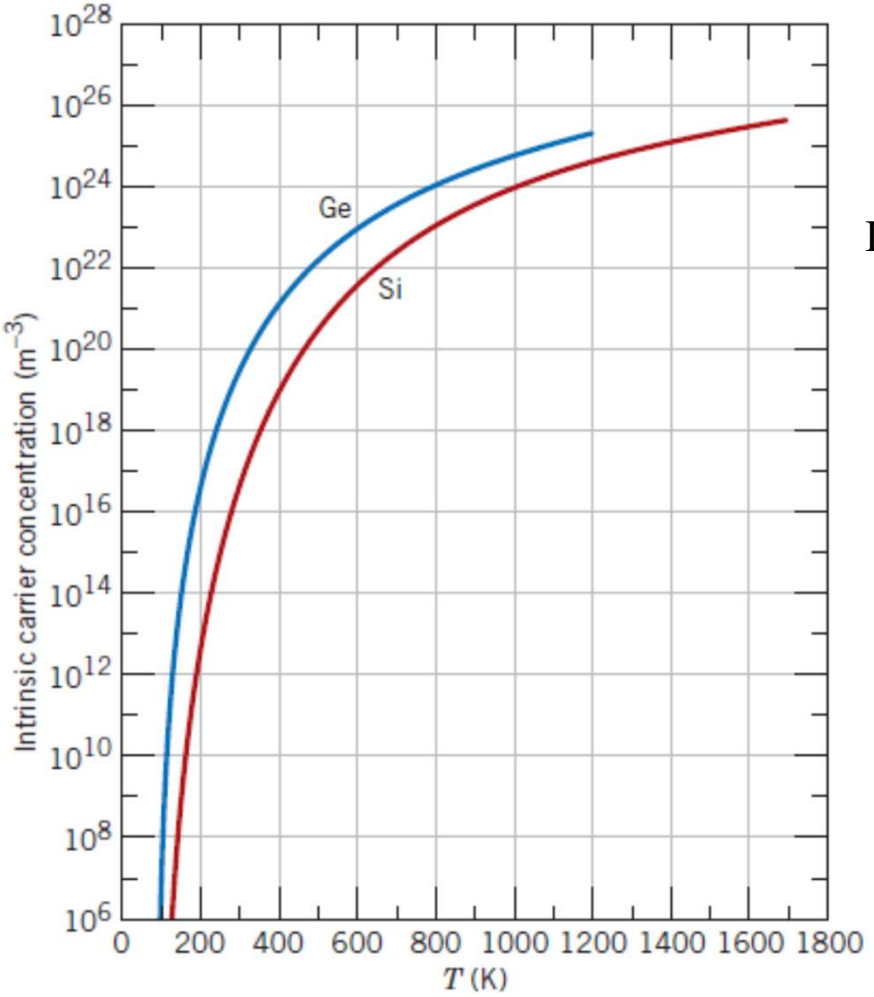
- The conductivity in p-*type* extrinsic semiconductor is

$$\sigma \cong p|e|\mu_h$$

Here, μ_h: Hole mobility

Temperature dependent Semiconductivity

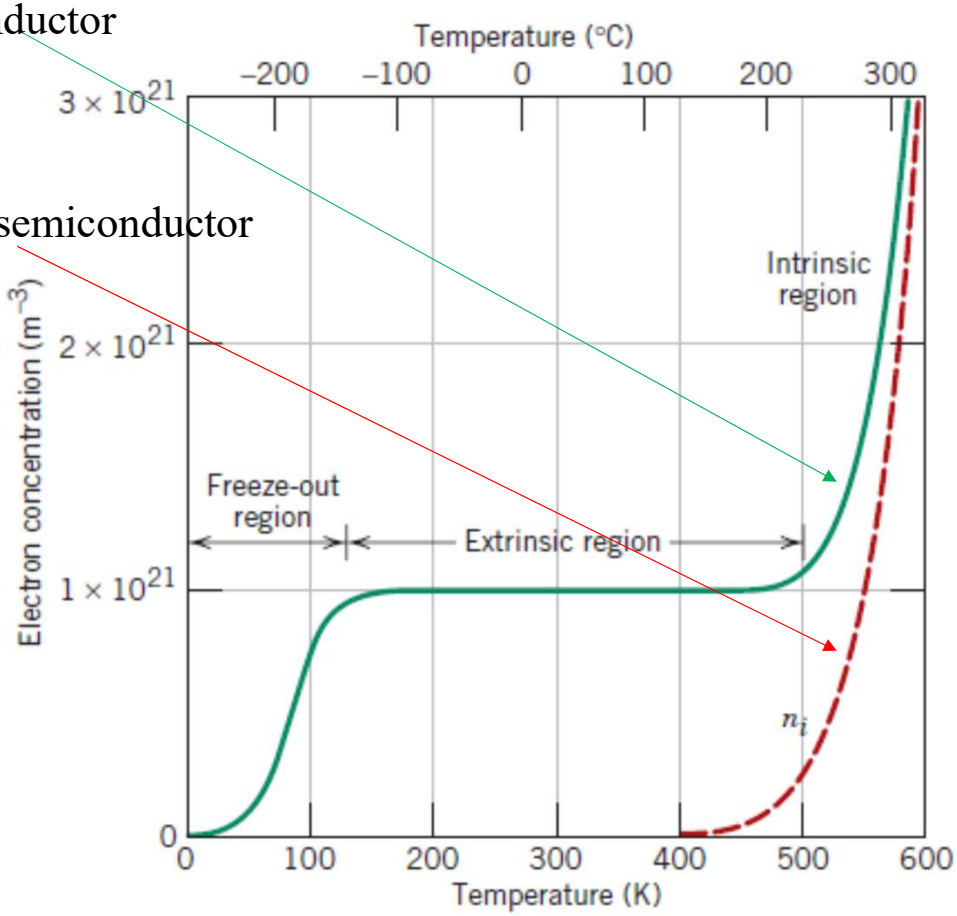
Intrinsic semiconductor



n–type Extrinsic semiconductor

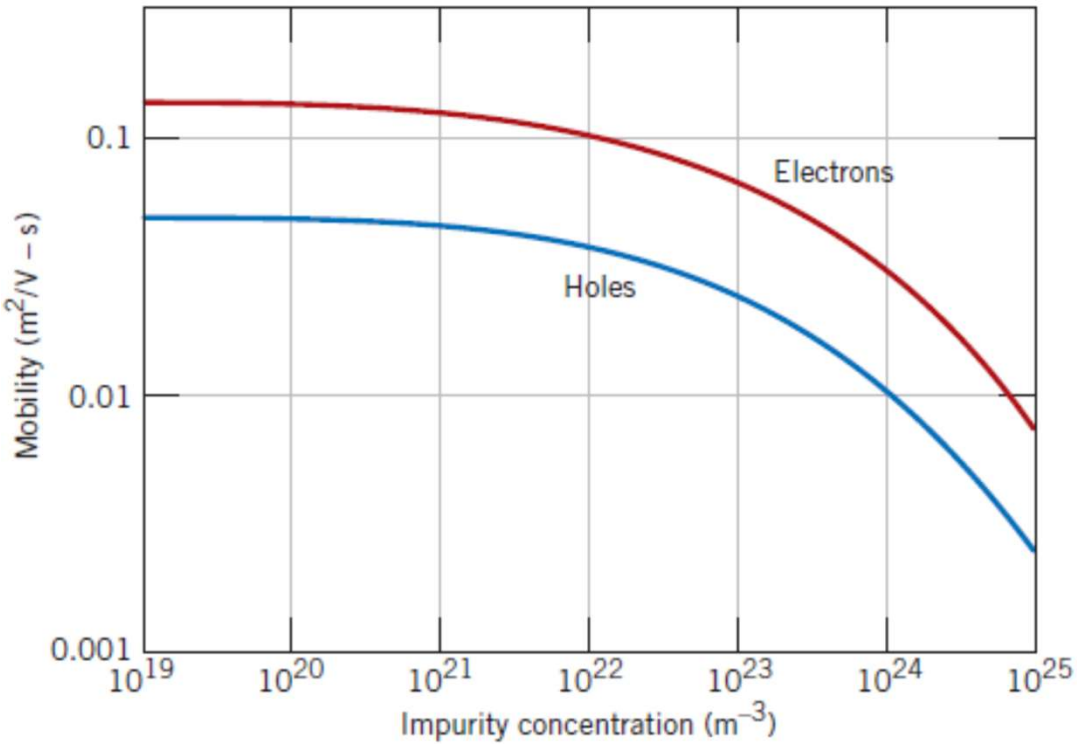
Intrinsic semiconductor

Intrinsic semiconductor



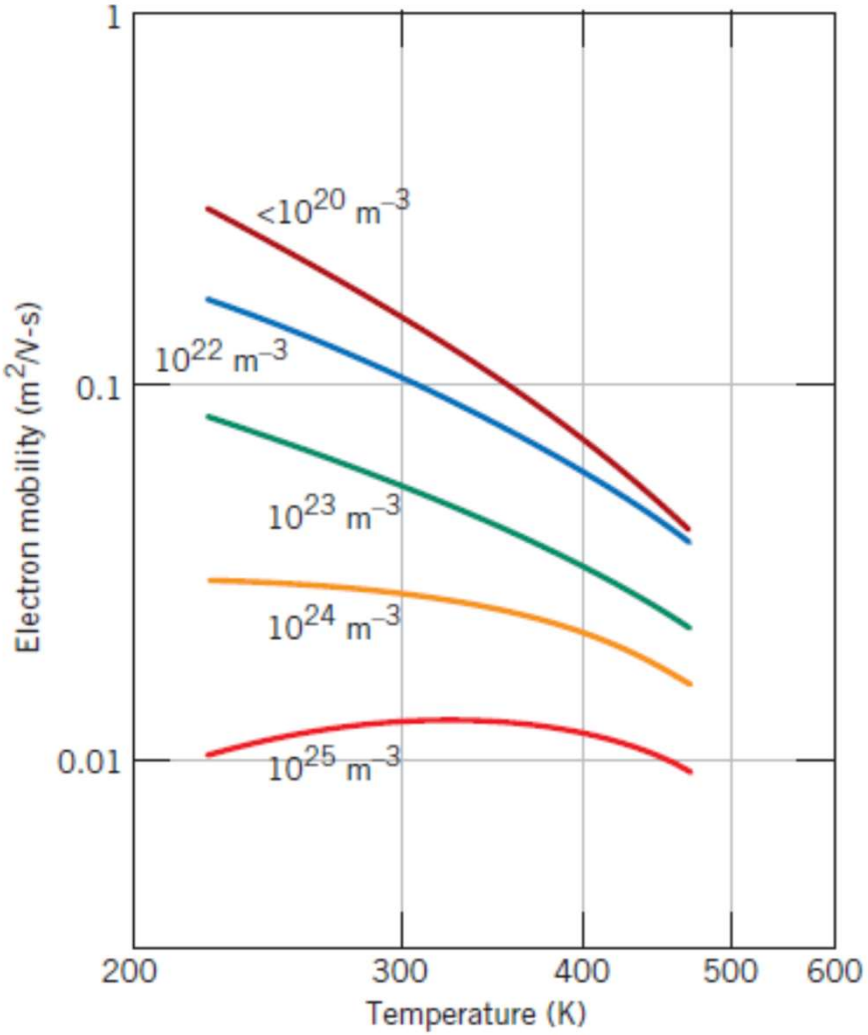
Factors affecting the Carrier mobility

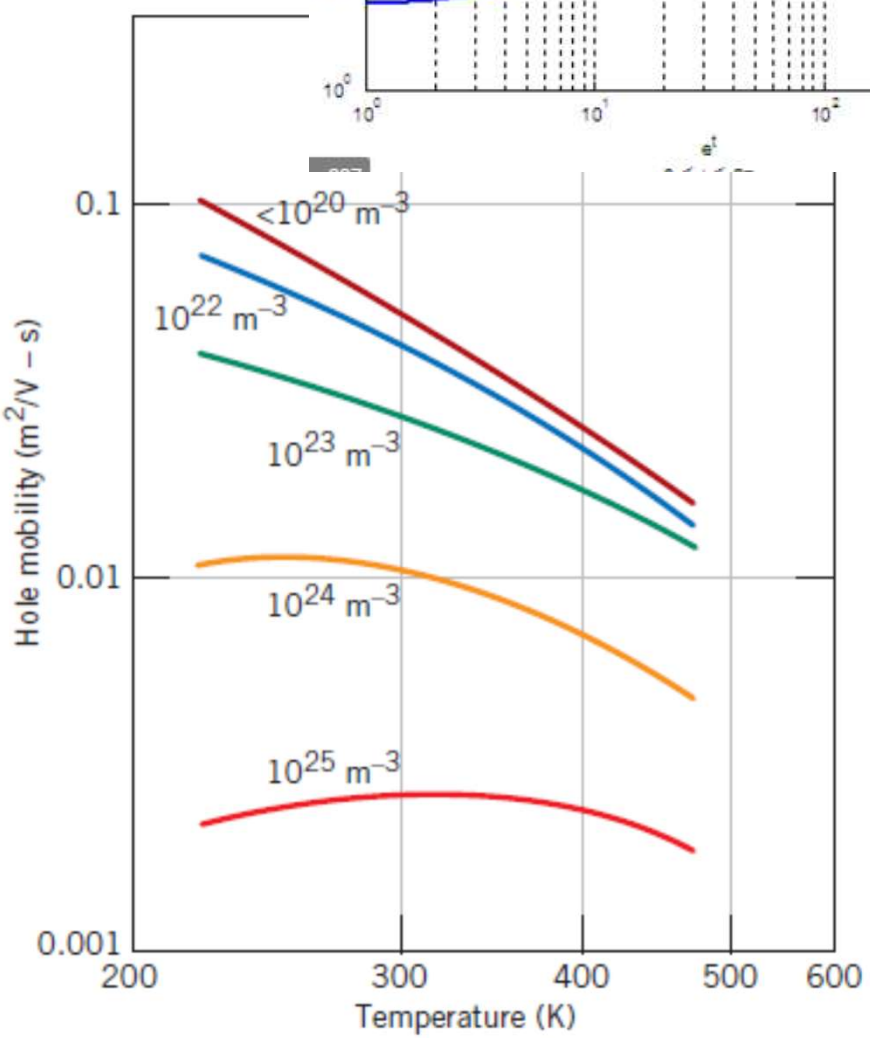
Influence of dopant concentration



Factors affecting the Carrier mobility

Influence of Temperature





Electrical Conductivity Determination for Intrinsic Silicon at 150°C

Calculate the electrical conductivity of intrinsic silicon at 150°C (423 K).

Solution

This problem may be solved using Equation 18.15, which requires specification of values for n_i, μ_e, and μ_h. From Figure 18.15, n_i for Si at 423 K is 4×10^{19} m^{-3}. Furthermore, intrinsic electron and hole mobilities are taken from the $<10^{20}$ m^{-3} curves of Figures 18.18*a* and 18.18*b*, respectively; at 423 K, $\mu_e = 0.06$ m^2/V·s and $\mu_h = 0.022$ m^2/V·s (realizing that both mobility and temperature axes are scaled logarithmically). Finally, from Equation 18.15, the conductivity is given by

$$\begin{aligned}\sigma &= n_i|e|(\mu_e + \mu_h) \\ &= (4 \times 10^{19}\ \text{m}^{-3})(1.6 \times 10^{-19}\ \text{C})(0.06\ \text{m}^2/\text{V·s} + 0.022\ \text{m}^2/\text{V·s}) \\ &= 0.52\ (\Omega\text{·m})^{-1}\end{aligned}$$

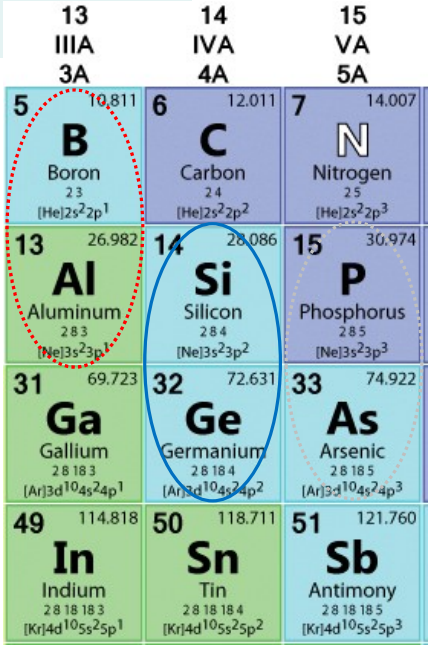
Room-Temperature and Elevated-Temperature Electrical Conductivity Calculations for Extrinsic Silicon

To high-purity silicon is added 10^{23} m^{-3} arsenic atoms.

(a) Is this material *n*-type or *p*-type?

(b) Calculate the room-temperature electrical conductivity of this material.

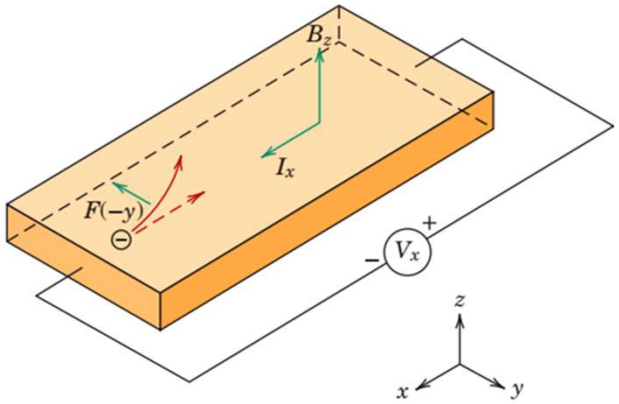
(c) Compute the conductivity at 100°C (373 K).



Hall Effect

- For some materials, it is on occasion desired to determine the material's majority charge carrier type, concentration, and mobility.
- To measure those properties, **Hall effect** experiment need to be conducted.
- **Hall effect:** If a magnetic field applied perpendicular to the direction of motion of a charged particle (current) exerts a force *(Lorentz force)* on the particle perpendicular to both the magnetic field and the particle motion directions.

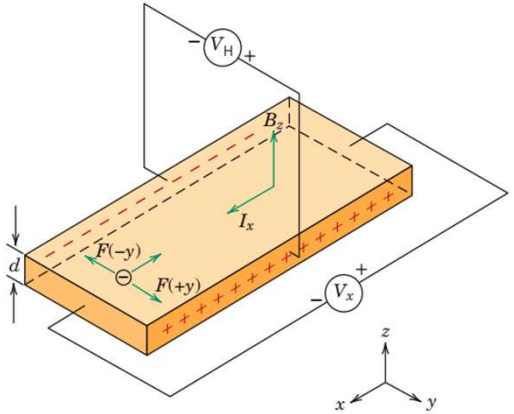
- Let us consider materials for which the electrical conduction arises from the motion of electrons (*n*-type semiconductors).
- Consider the parallelepiped specimen shown in Fig. that is referenced to an *x*-*y*-*z* Cartesian coordinate system.



- An external voltage (V_x), is applied so as to give rise to a current (I_x) that flows in the +*x* direction as shown.
- The electron motion is in the -*x* direction (dashed arrow).
- Upon the imposition of a magnetic field in the +*z* direction (B_z), a force, the Lorentz force, *F*(-*y*) is brought to bear on an electron in the -*y* direction.

Hall Effect

- Electrons continue to pile up on this specimen face, while at the same time the opposite (front) specimen face assumes a net positive charge as a result of the depletion of electrons from this region as shown in in Fig.
- This situation leads to the creation of a voltage (V_H) between these charged specimen faces.

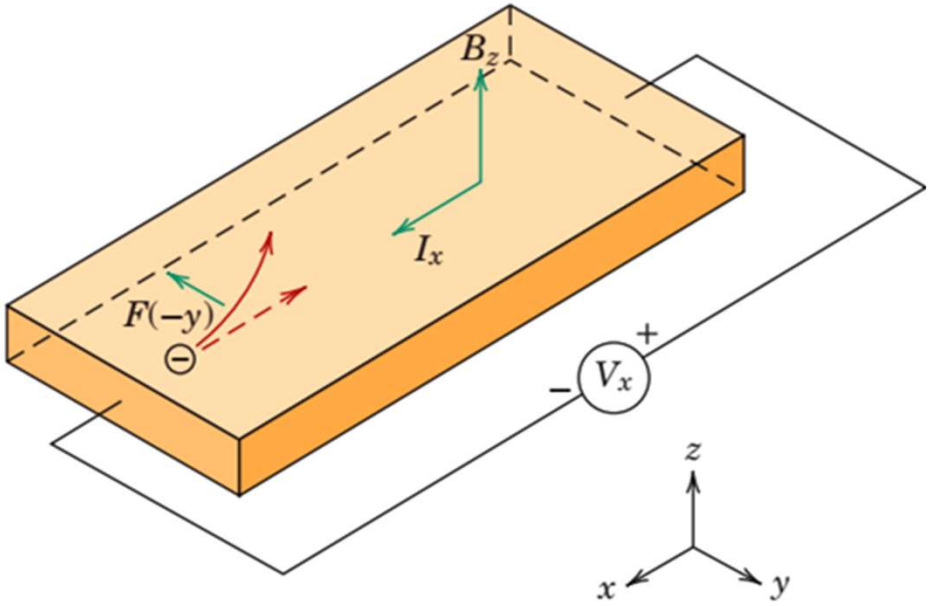


- In addition, to another force [$F(+y)$] imposed on the electrons participating in the I_x current, which is in a direction opposite to that of $F(-y)$.
- Ultimately, a condition of steady-state is achieved when $F(+y) = F(-y)$ and electron motion resumes in the $-x$ direction, as noted by the arrow.
- From the magnitude and sign of the Hall voltage (V_H) it is possible to determine the type of charger carrier, charge carrier concentration and mobility.
- For a negative V_H, electrons are the charge carriers.
- Furthermore, by equating expressions for $F(+y)$ and $F(-y)$, it is possible to derive an equation for the magnitude of V_H, which is as follows:

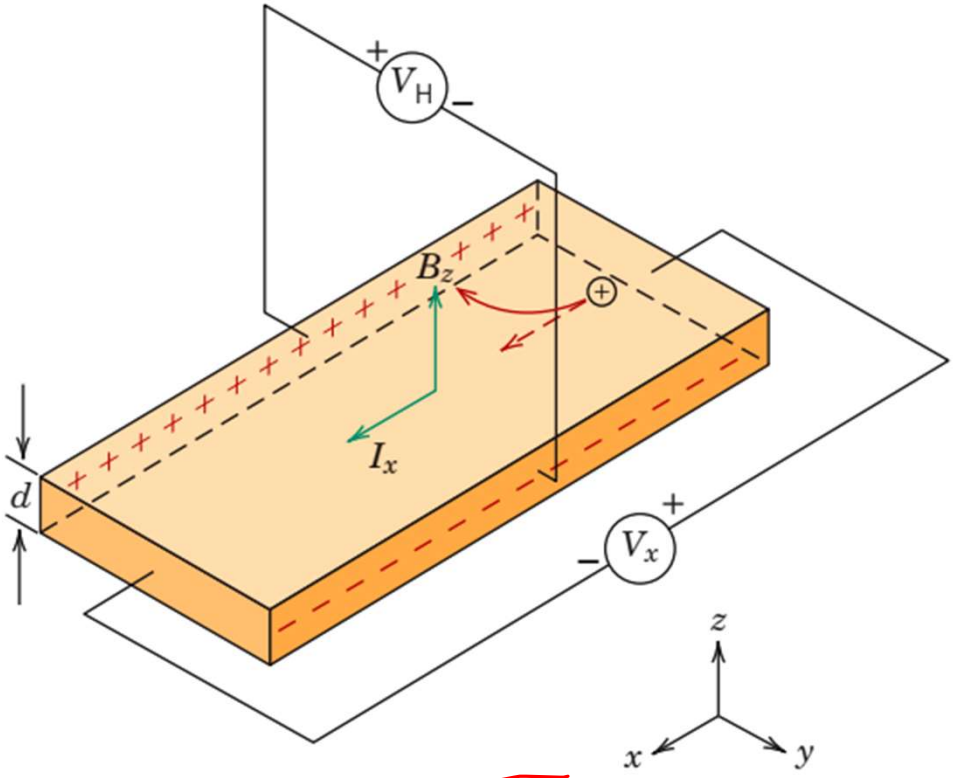
$$V_H = \frac{R_H I_x B_z}{d}$$

Where, d is the specimen thickness

R_H is termed the *Hall coefficient,* which is a constant for a specific material



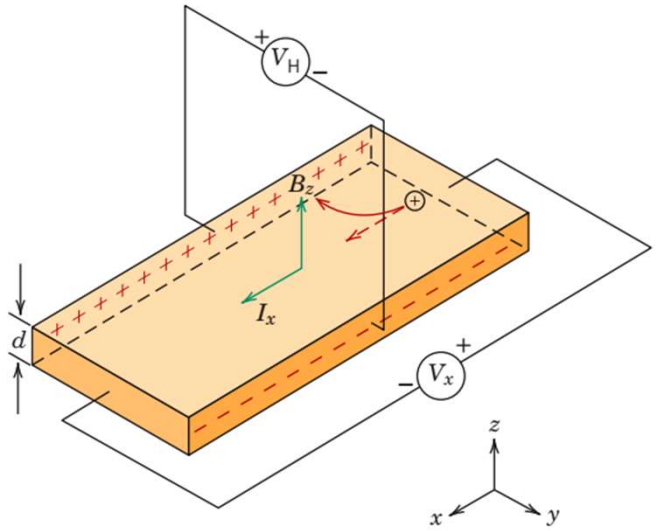
N TYPE



P TYPE

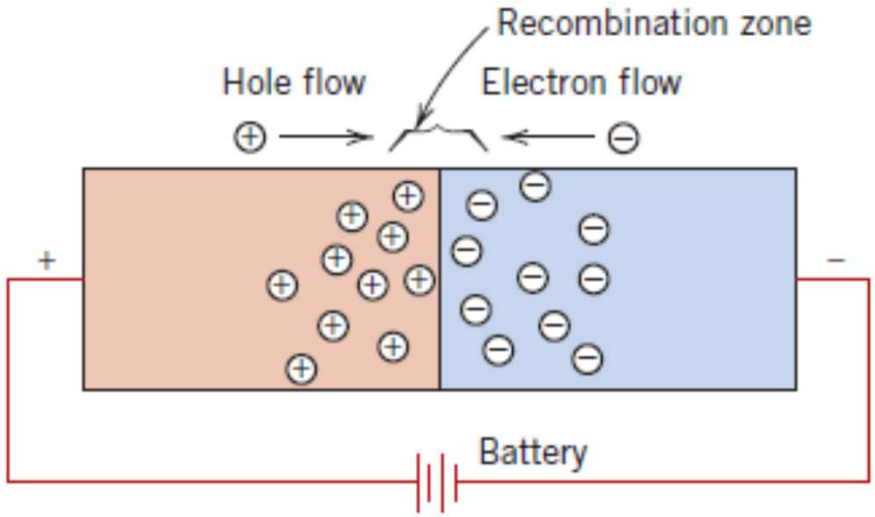
Hall Effect

- For metals and *n*-type semiconductors, in which conduction is by electrons, R_H is negative and is given by $$R_H = \frac{1}{n|e|}$$
- The electron mobility μ_e is $$\mu_e = \frac{\sigma}{n|e|}$$
- From R_H, it may rewrite as $$\mu_e = |R_H|\sigma$$
- Thus, the magnitude of μ_e also be determined if the conductivity σ has also been measured.

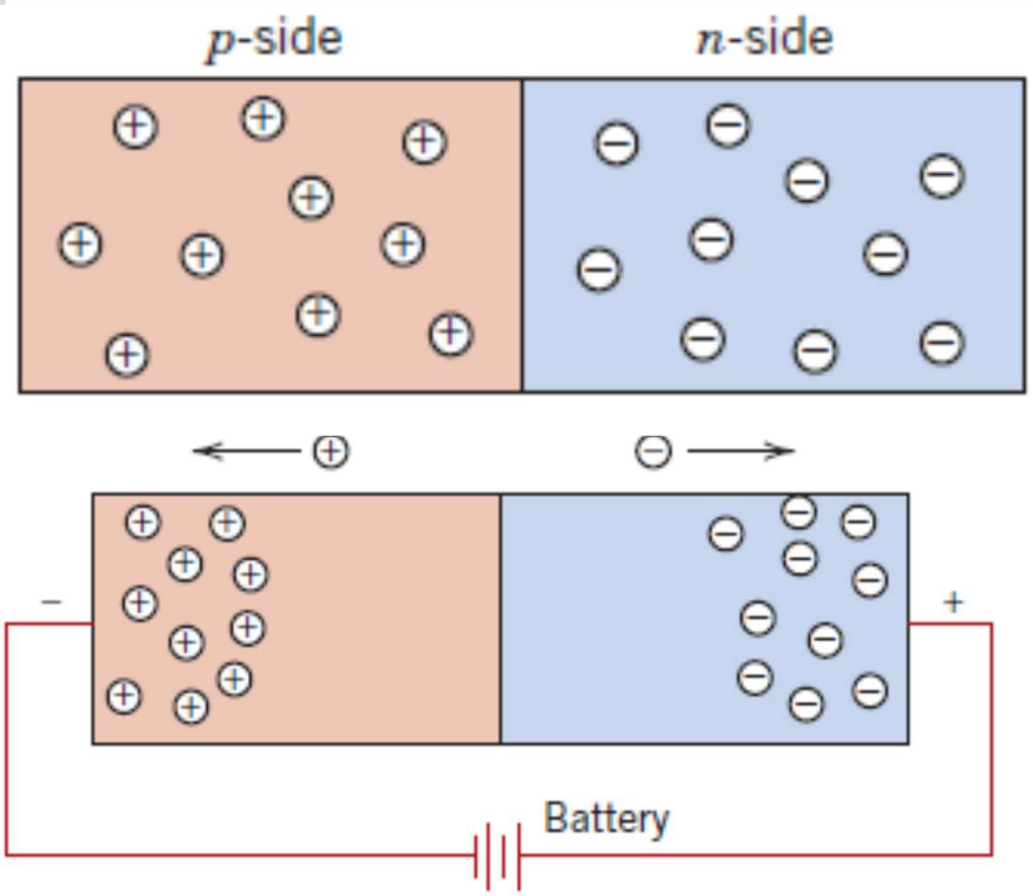


- For *p*-type semiconductors, conduction arises from the motion of holes, the electrical charge on each hole is positive, and hole motion is in the +*x* direction (opposite to that for electrons) as noted in Fig.
- Consequently, the Lorentz force imposed on holes is in the same direction as for electrons, toward the back-specimen face.
- Thus, the sign of V_H is positive, which is opposite to that for metals and *n*-type semiconductors.

Semiconductor Devices - – PN Junction Diode

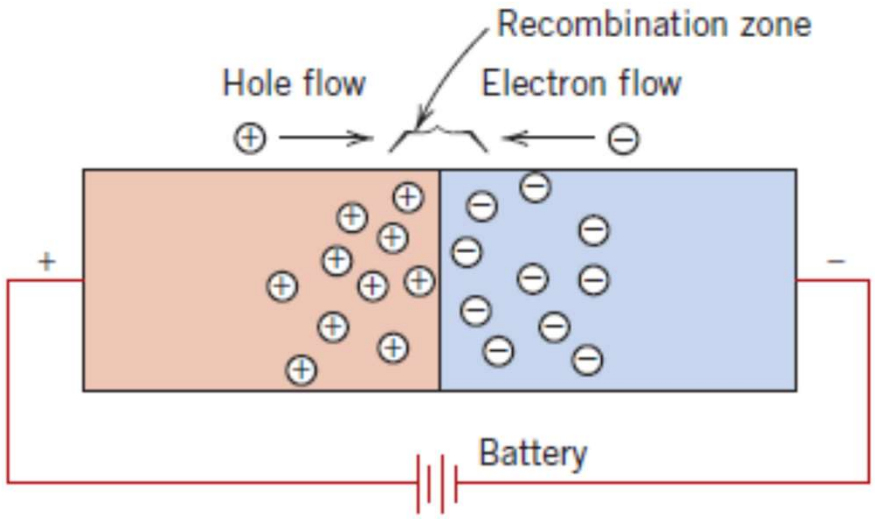


Forward Bias

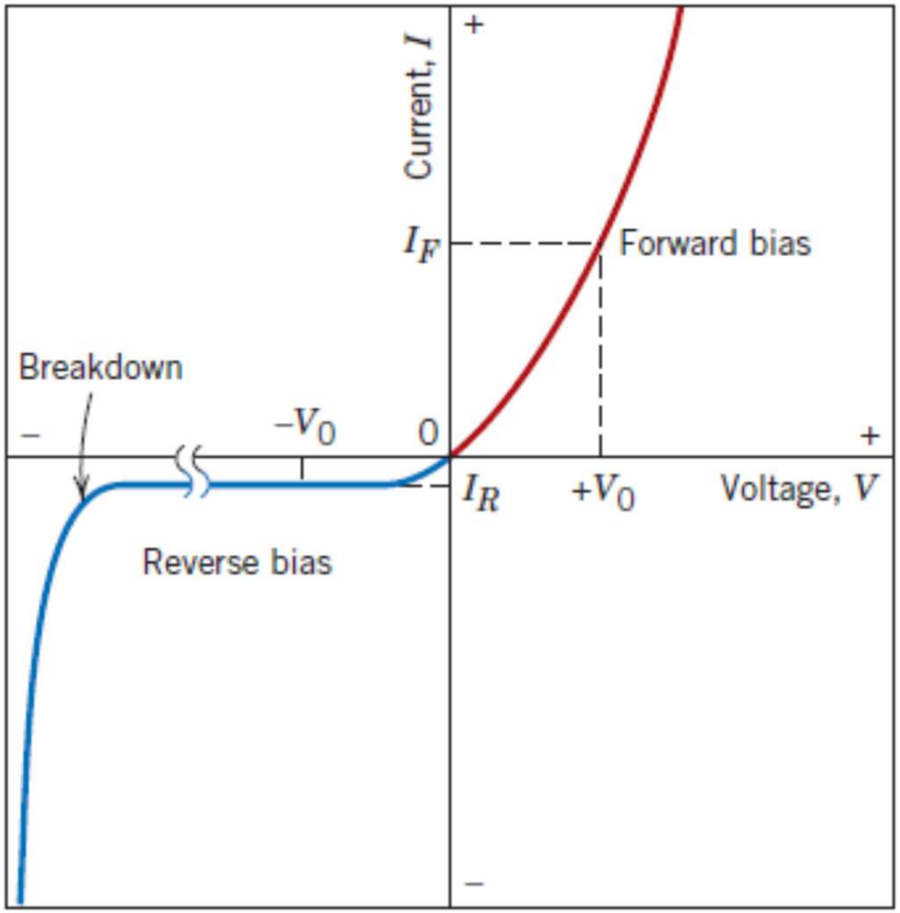


Reverse Bias

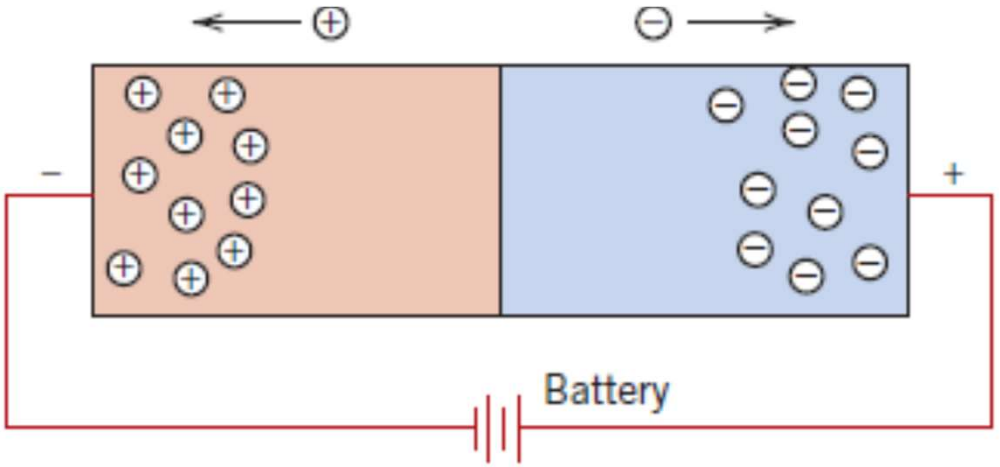
Semiconductor Devices – PN Junction Diode



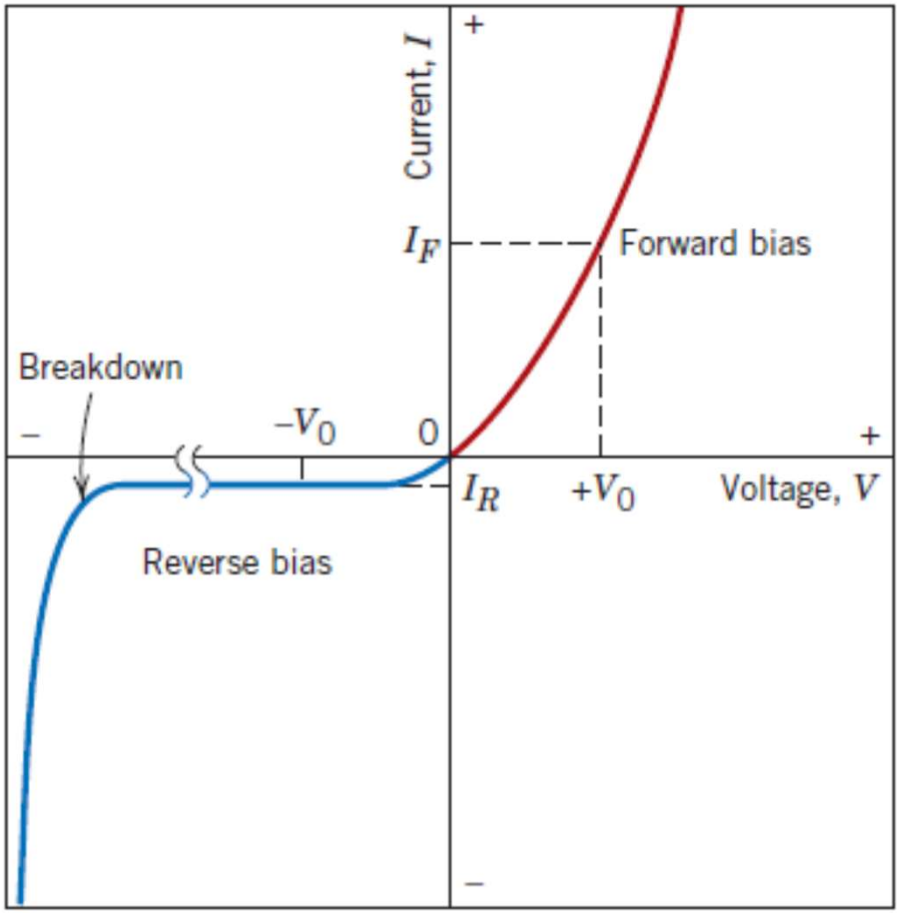
Forward Bias



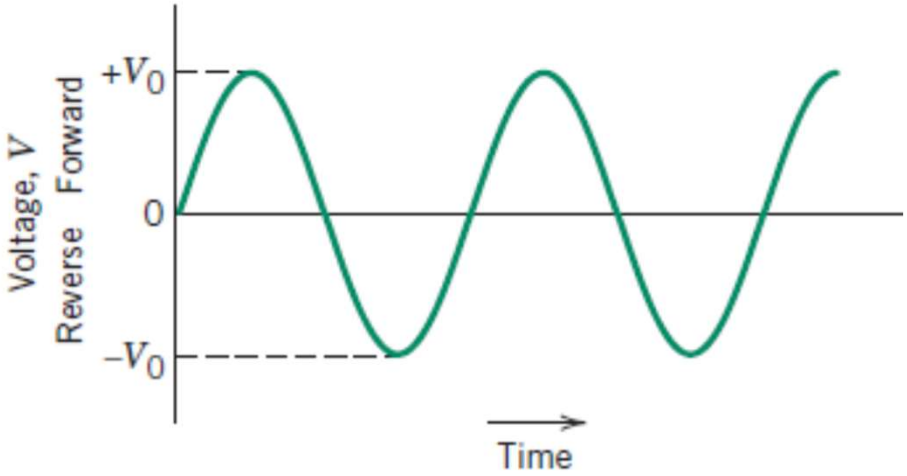
Semiconductor Devices



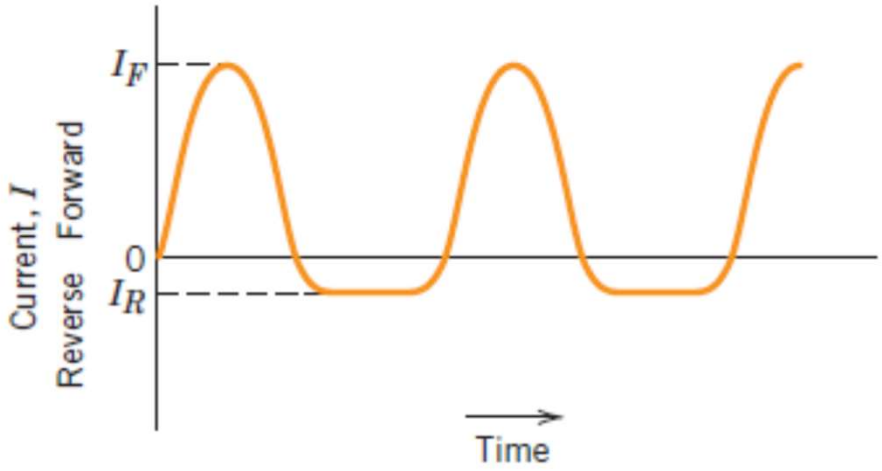
Reverse Bias



Semiconductor Devices



Input Voltage

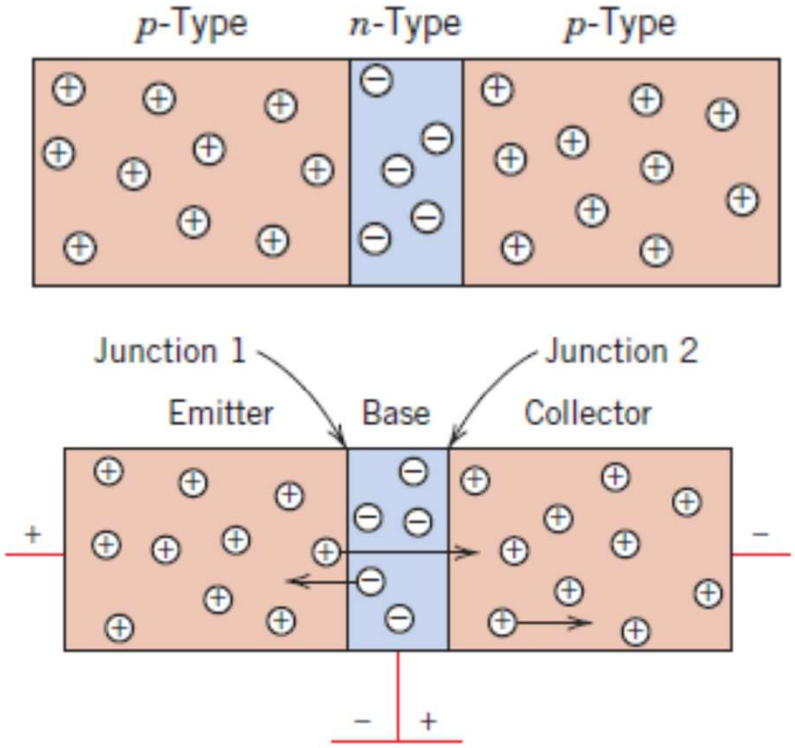


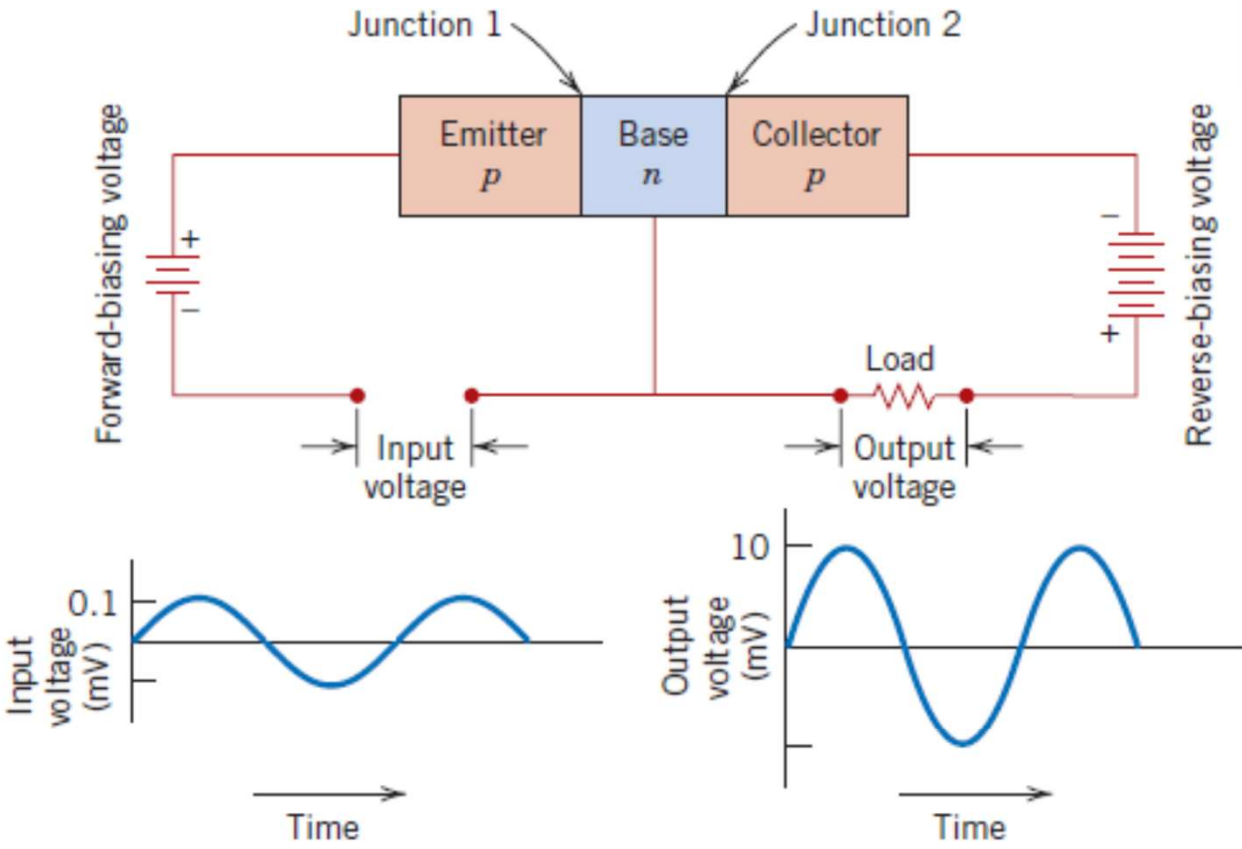
Output Current

- Rectifying a voltage: turning AC into DC voltages.
- Drawing signals from a supply.
- Controlling the size of a signal.
- Mixing (multiplexing) signals.

The Transistor

- **Junction or Bimodal Transistors**
- Metal Oxide Semiconductors Field–Effect Transistor (MOSFET)



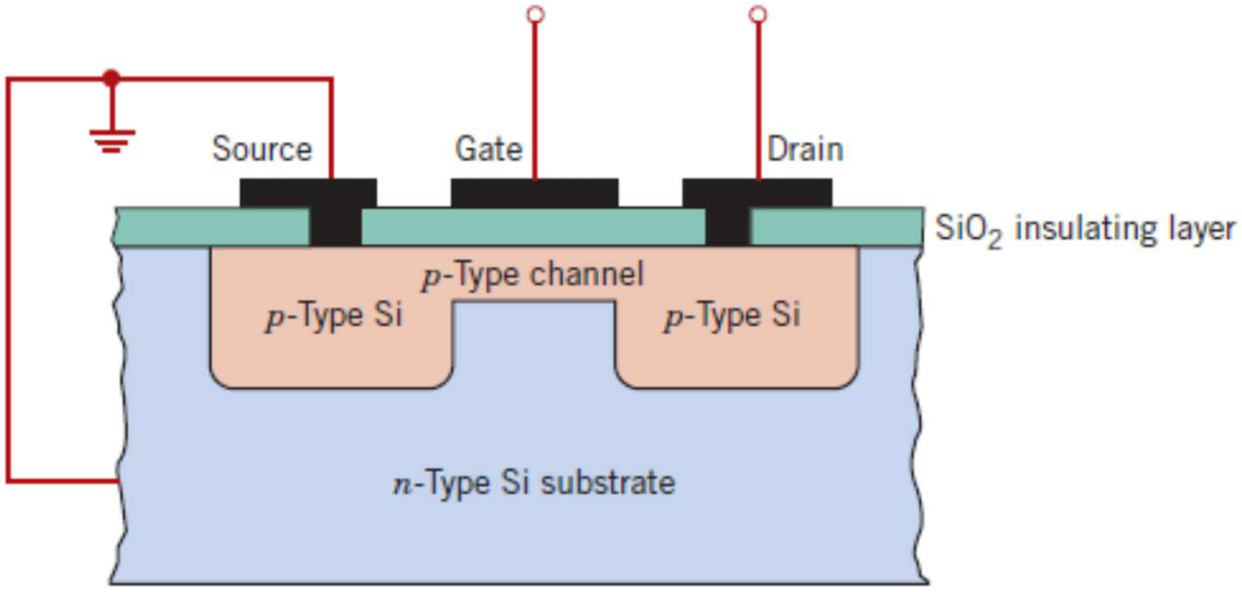


The Transistor

- Junction or Bimodal Transistors
- Metal Oxide Semiconductors Field–Effect Transistor (**MOSFET**)

Transistors have extensive uses in our day to day life.

They are used in nearly every kind of circuit in order to perform a function. A few applications of transistors are: **switches, amplifiers, oscillators, modulators, detectors**



Schematic cross – section of MOSFET

Most commercial Inverters are packed with MOSFETs for driving stage because **it is very efficient in switching,** less resistance path between source and drain terminal which translates to less heat.

Dielectric Behaviour - Capacitor

- When a voltage is applied across a capacitor, one plate becomes positively charged and the other negatively charged, with the corresponding electric field directed from the positive to the negative plates.
- The **capacitance** *C* is related to the quantity of charge stored on either plate *Q* by:

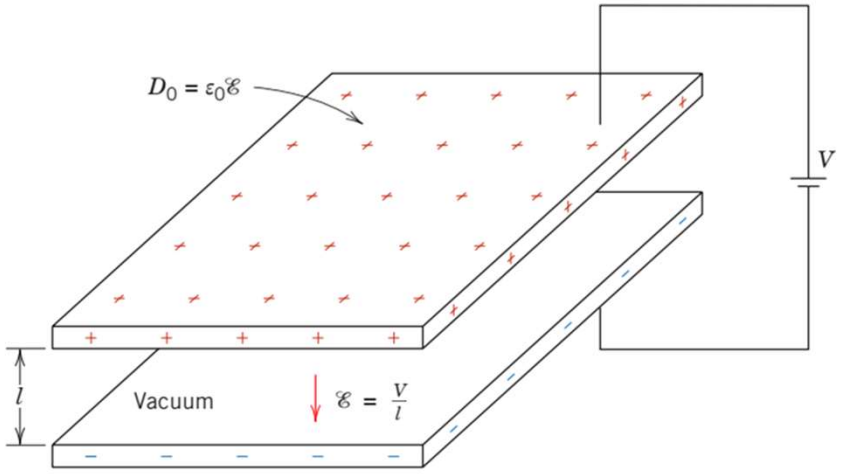
$$C = \frac{Q}{V}$$

Where, *V* is the voltage applied across the capacitor.
The units are coulombs per volt, or farads (F)

- Now, consider a parallel-plate capacitor with a vacuum in the region between the plates (Fig).
- The capacitance may be computed from the relationship:

$$C = \varepsilon_0 \frac{A}{l}$$

Here *A* represents the area of the plates
l is the distance between them.
ε_0: **Permittivity** of a vacuum
$= 8.85 \times 10^{-12}$ F/m



A parallel-plate capacitor when a vacuum is present

Dielectric Behaviour - Capacitor

- If a dielectric material is inserted into the region within the plates (Fig.), then

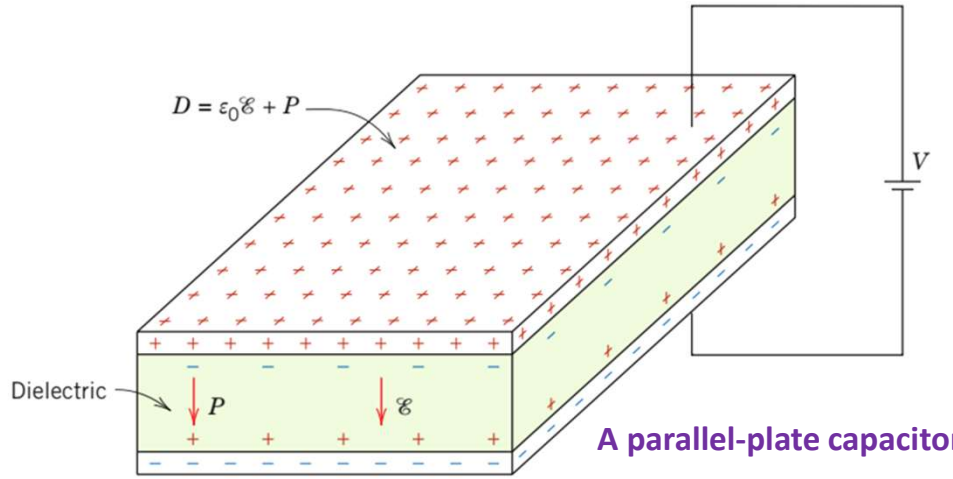
$$C = \varepsilon \frac{A}{l}$$

where ε is the permittivity of this dielectric medium, which is greater in magnitude than ε_0

- The relative permittivity ε_r, often called the **dielectric constant,** is equal to the ratio:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

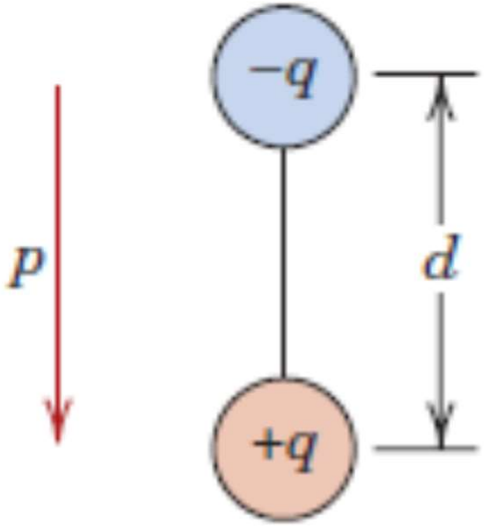
It is greater than unity and represents the increase in charge-storing capacity upon insertion of the dielectric medium between the plates.

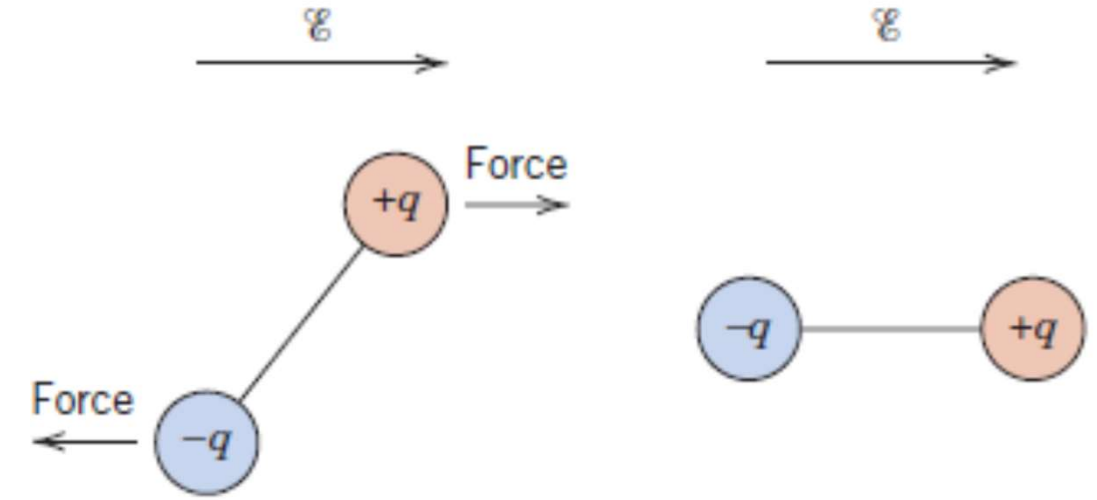


A parallel-plate capacitor when a dielectric material is present

- The dielectric constant is one material property of prime consideration for capacitor design.

Field Vectors and Polarization





Dipole getting aligned along the direction of electric field – Polarization

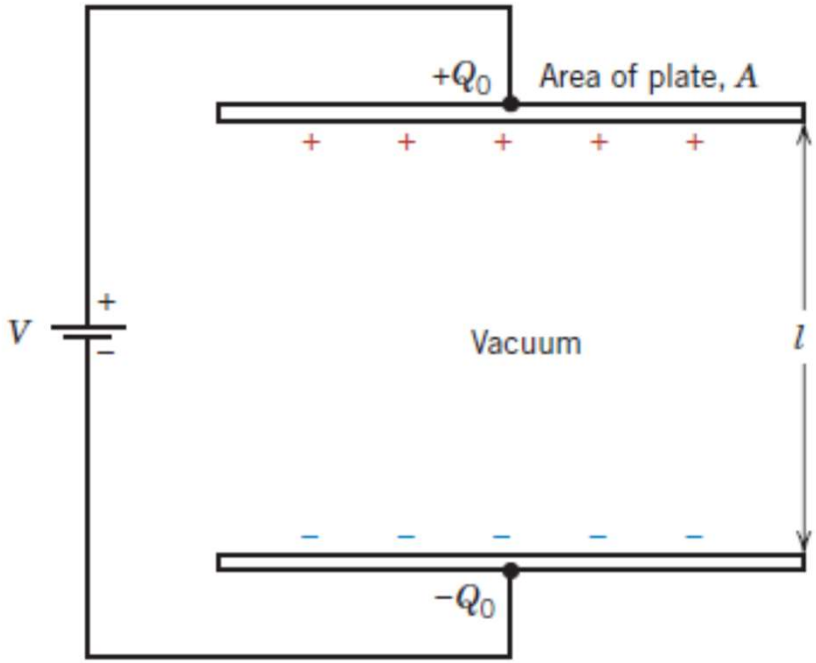
$$p = qd$$

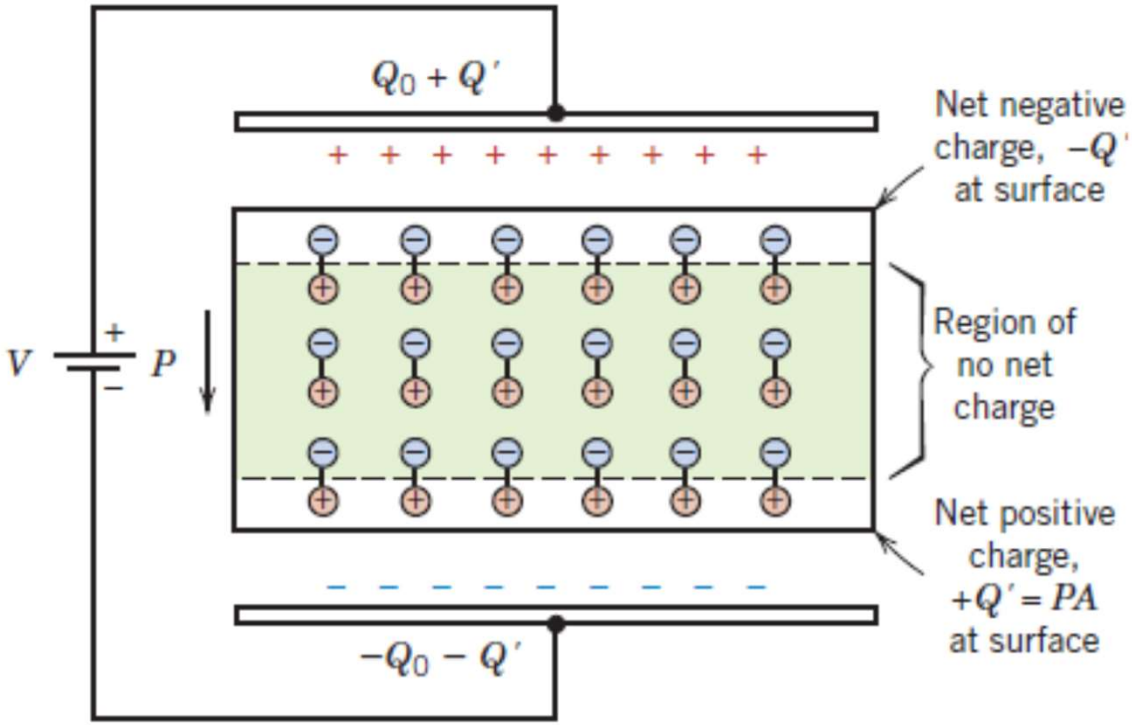
Field Vectors and Polarization

Surface charge per unit area or charge density D is given by,

$$D_0 = \epsilon_0 E \text{ in vacuum}$$
$$D = \epsilon E \text{ for any dielectric material.}$$

D is sometimes called dielectric displacement.





$$D = \epsilon_0 E + P;\ P = \epsilon_0 (\epsilon_r - 1) E$$

Frequency dependence of dielectric constant

Material	Dielectric Constant		Dielectric Strength (V/mil)[a]
	60 Hz	1 MHz	
	Ceramics		
Titanate ceramics	—	15–10,000	50–300
Mica	—	5.4–8.7	1000–2000
Steatite (MgO–SiO_2)	—	5.5–7.5	200–350
Soda–lime glass	6.9	6.9	250
Porcelain	6.0	6.0	40–400
Fused silica	4.0	3.8	250
	Polymers		
Phenol-formaldehyde	5.3	4.8	300–400
Nylon 6,6	4.0	3.6	400
Polystyrene	2.6	2.6	500–700
Polyethylene	2.3	2.3	450–500
Polytetrafluoroethylene	2.1	2.1	400–500

Field Vectors and Polarization

Consider a parallel-plate capacitor having an area of 0.0006 m^2 and a plate separation of 0.002 m across which a potential of 10 V is applied. If a material having a dielectric constant of 6.0 is positioned within the region between the plates, compute

a) The capacitance.
b) The magnitude of the charge stored on each plate.
c) The dielectric displacement D.
d) The polarization.

$$\varepsilon = \varepsilon_r \varepsilon_0 = (6.0)(8.85 \times 10^{-12}\ \text{F/m})$$
$$= 5.31 \times 10^{-11}\ \text{F/m}$$

Thus, the capacitance is given by

$$C = \varepsilon \frac{A}{l} = (5.31 \times 10^{-11}\ \text{F/m}) \left(\frac{6.45 \times 10^{-4}\ \text{m}^{-2}}{20 \times 10^{-3}\ \text{m}} \right)$$
$$= 1.71 \times 10^{-11}\ \text{F}$$

$$Q = CV = (1.71 \times 10^{-11}\ \text{F})(10\ \text{V}) = 1.71 \times 10^{-10}\ \text{C}$$

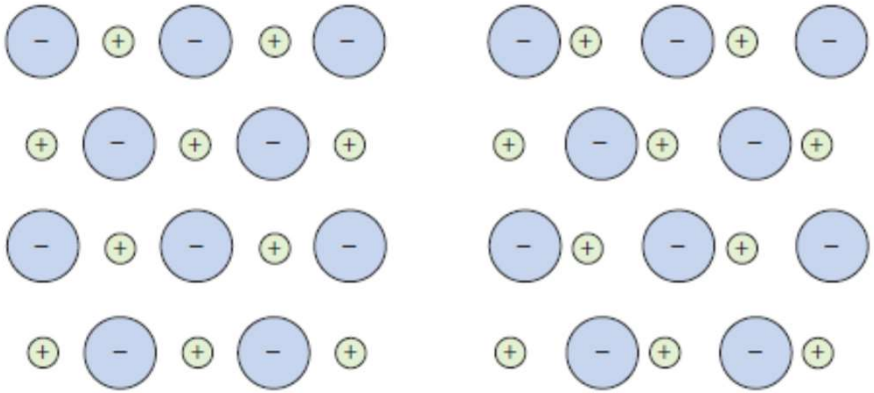
$$D = \varepsilon \mathscr{E} = \varepsilon \frac{V}{l} = \frac{(5.31 \times 10^{-11}\ \text{F/m})(10\ \text{V})}{2 \times 10^{-3}\ \text{m}}$$
$$= 2.66 \times 10^{-7}\ \text{C/m}^2$$

$$P = D - \varepsilon_0 \mathscr{E} = D - \varepsilon_0 \frac{V}{l}$$
$$= 2.66 \times 10^{-7}\ \text{C/m}^2 - \frac{(8.85 \times 10^{-12}\ \text{F/m})(10\ \text{V})}{2 \times 10^{-3}\ \text{m}}$$
$$= 2.22 \times 10^{-7}\ \text{C/m}^2$$

Types of Polarization

- Electronic Polarization
- Ionic Polarization
- Orientation Polarization

Electronic polarization that results from the distortion of an atomic electron cloud by an electric field,. found in all dielectric materials exists only when electric field is present.



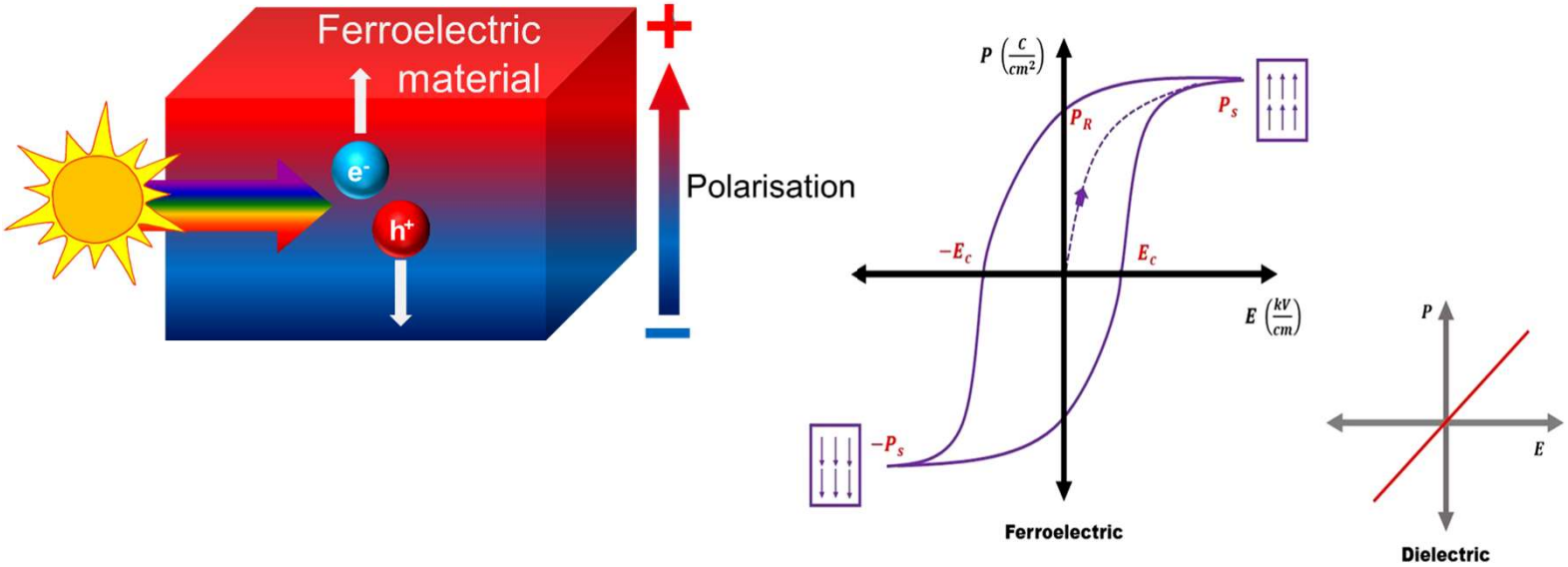
Ionic polarization that results from the relative displacements of electrically charged ions in response to an electric field.

Response of permanent electric dipoles (arrows) to an applied electric field, producing orientation polarization. alignment is counteracted by thermal vibrations of the atoms, such that polarization decreases with increasing temperature

Ferroelectricity

- Below certain temperature, it is found that some materials spontaneously acquire an electric dipole-moment Eg. Barium titanate.
- These materials are called as ferroelectric materials or ferroelectrics.
- The temperature at which ferroelectric property of the material disappears is called as *ferroelectric Curie temperature*.

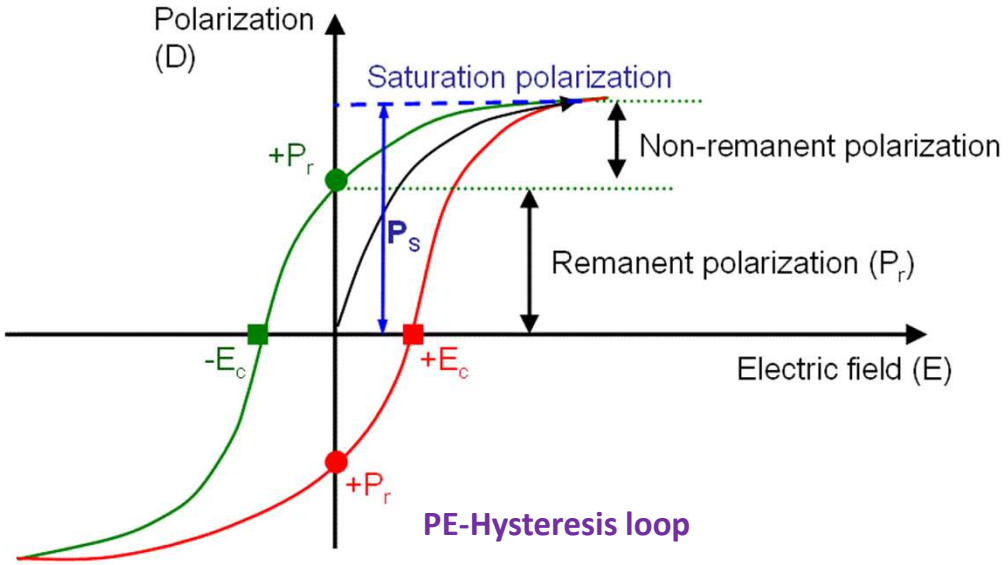
➢ Ferroelectric materials are anisotropic crystals, which exhibit a *hysteresis curve* **P versus E** which can be explained by domain hypothesis.



Ferroelectricity

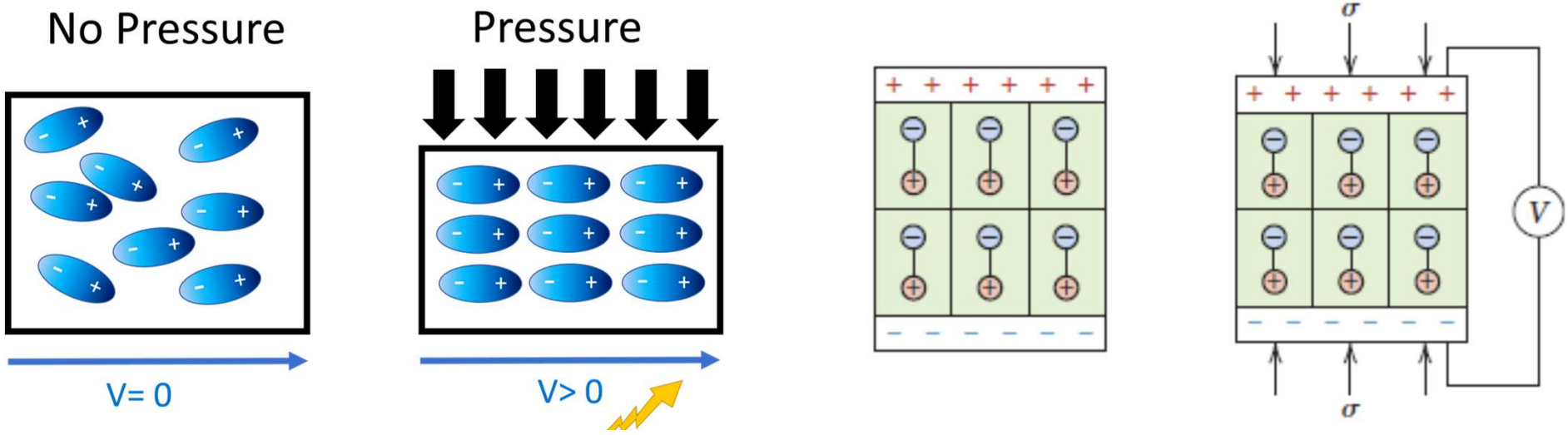
Consequently, capacitors made from these materials can be significantly smaller than capacitors made from other dielectric materials (high dielectric constant).

Ex. Rochelle salt (NaKC4H4O6.4H2O), potassium dihydrogen phosphate (KH2PO4), potassium niobate (KNbO3), and lead zirconate–titanate (Pb[ZrO3, TiO3])



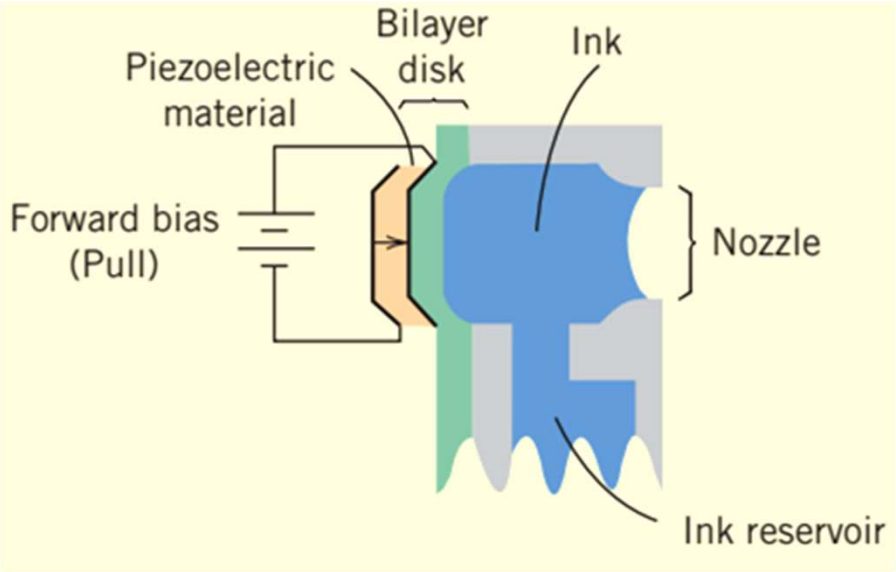
Piezoelectricity

- Single crystal of quartz is used for *filter*, *resonator* and *delay line* applications.
- Rochelle salt is used as *transducer in gramophone pickups*, *ear phones*, *hearing aids*, *microphones* etc.
- ✓ The commercial ceramic materials are based on barium titanate, lead zirconate and lead titanate.
- ✓ They are used for *high voltage generation* (gas lighters), *accelerometers*, *transducers* etc.
- ✓ Piezo electric semiconductors such as GaS, ZnO & CdS are used as *amplifiers of ultrasonic waves*.



Piezoelectric Ceramic Ink-Jet Printer Heads Case Study

- Piezoelectric materials are used in one kind of ink-jet printer head that has components and a mode of operation represented in Fig.

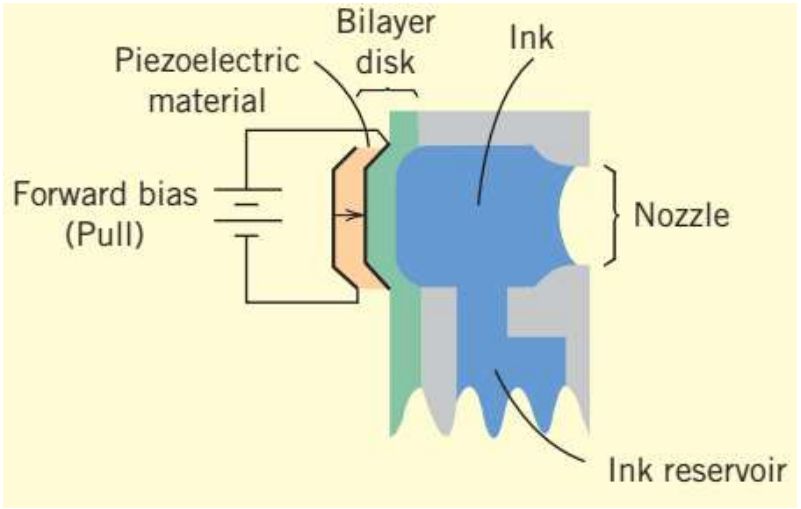


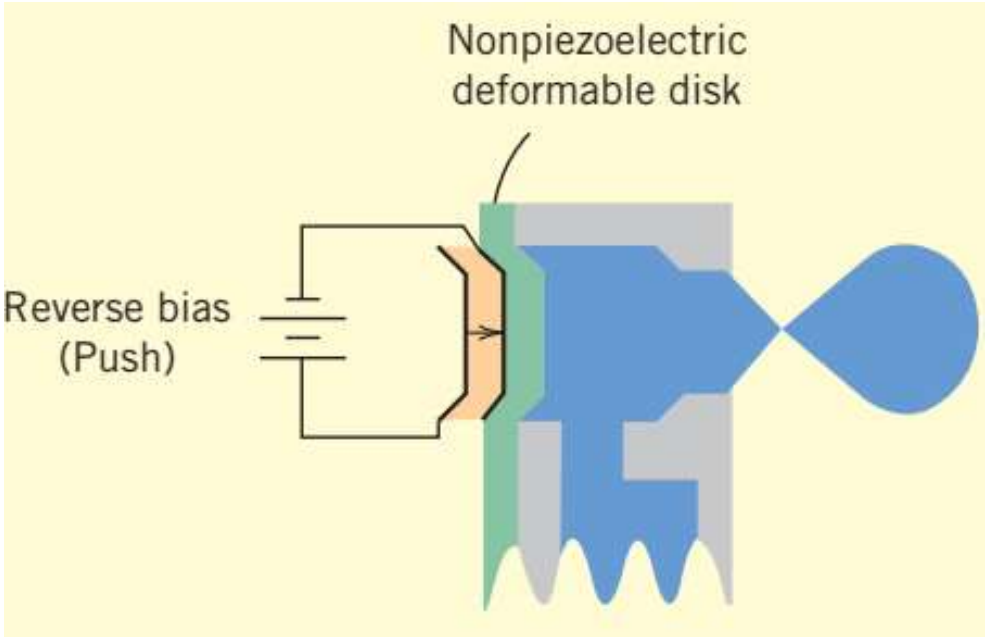
Imposing a forward-bias voltage draws ink into the nozzle chamber as the bi-layer disk flexes in one direction

- One head component is a flexible, bi-layer disk that consists of a piezoelectric ceramic (*orange region*) bonded to a non-piezoelectric deformable material (*green region*)
- Liquid ink and its reservoir are represented by *blue areas*.
- Short, horizontal arrows within the piezoelectric note the direction of the permanent dipole moment.
- Fig. shows how the imposition of forward bias voltage causes the bi-layer disk to flex in such a way as to pull ink from the reservoir into the nozzle chamber.

Piezoelectric Ceramic Ink-Jet Printer Heads Case Study

- Reversing the voltage bias forces the bi-layer disk to bend in the opposite direction, toward the nozzle, so as to eject a drop of ink (Fig).

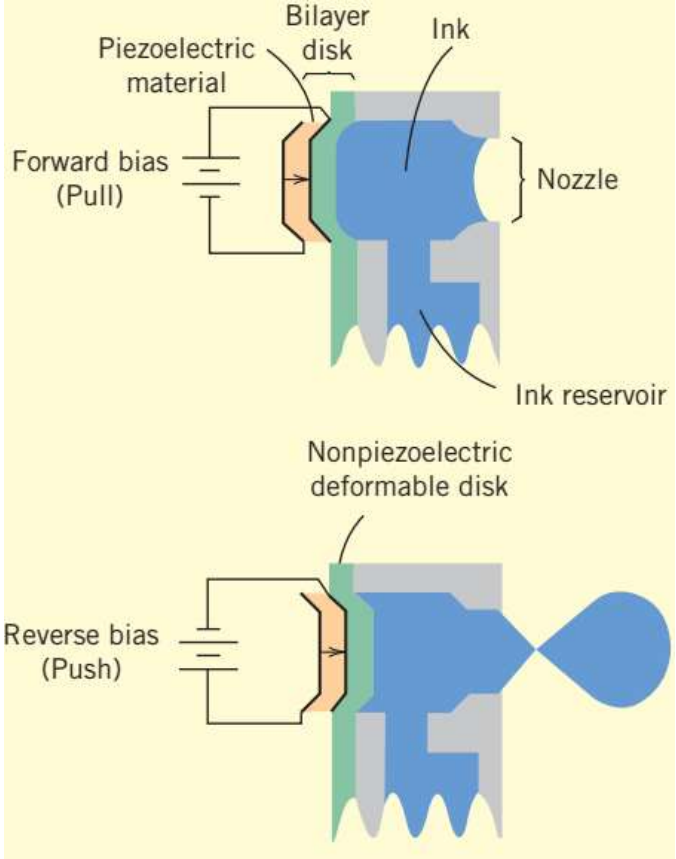


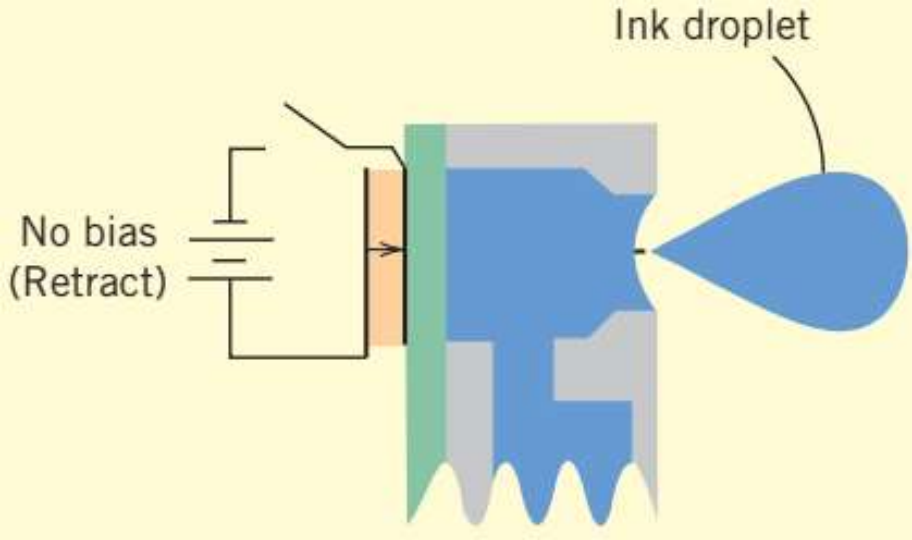


Ejection of an ink drop by reversing the voltage bias and forcing the disk to flex in the opposite direction

Piezoelectric Ceramic Ink-Jet Printer Heads Case Study

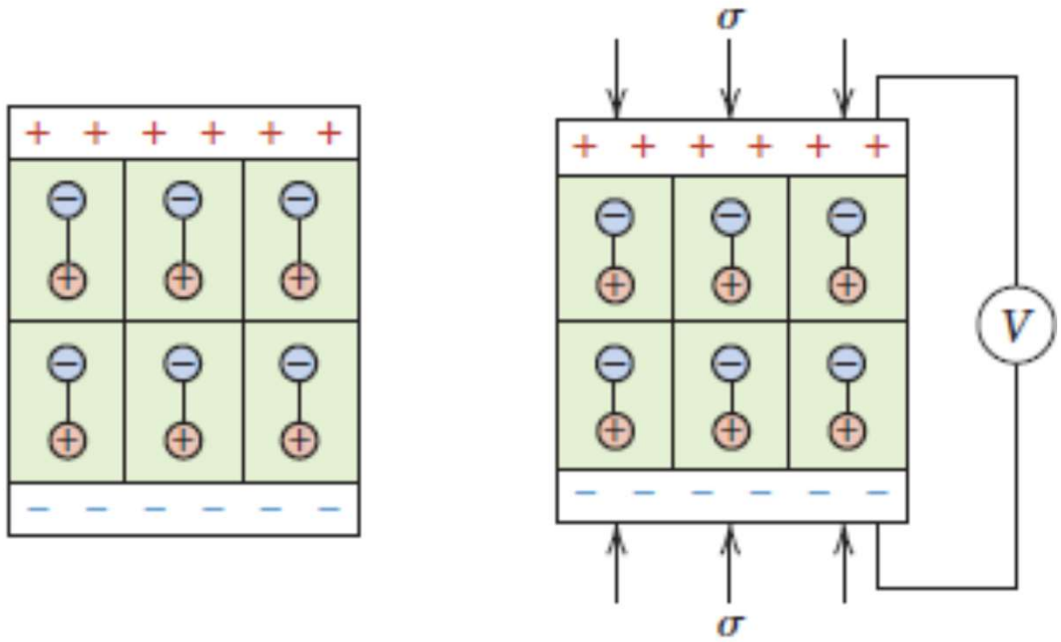
- Reversing the voltage bias forces the bi-layer disk to bend in the opposite direction, toward the nozzle, so as to eject a drop of ink (Fig).





Removing the voltage retracts the bi-layer disk to its unbent configuration in preparation for the next sequence

Piezoelectricity

Application of stress induces voltage. Applications–transducers, phonograph cartridges, speakers, audible alarms.

Titanates of barium and lead ($BaTiO_3$ and $PbTiO_3$), lead zirconate ($PbZrO_3$), lead zirconate–titanate (PZT) [$Pb(Zr,Ti)O_3$], and potassium niobate ($KNbO_3$)