Current Flow in Semiconductors

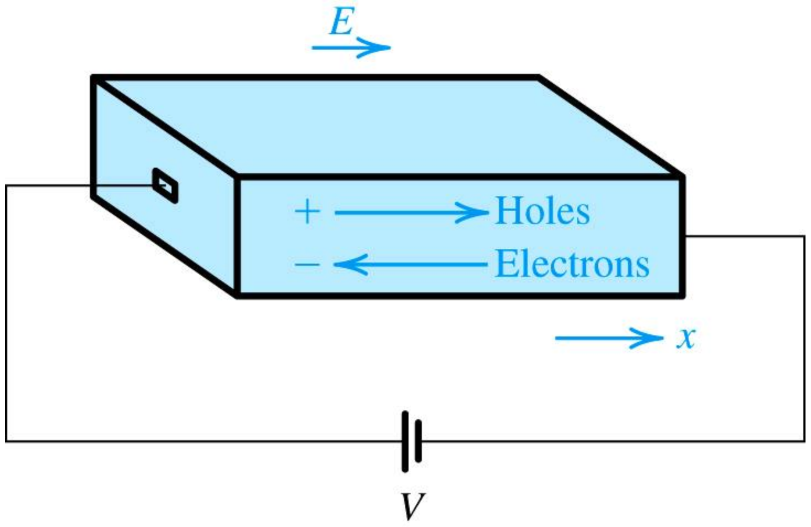
Drift Current

- When an electrical field (E) is applied to a semiconductor crystal, holes are accelerated in the direction of E, free electrons are accelerated in the direction opposite to that of E
- The velocity of holes and electrons defined by

$$v_{p\text{-}drift} \ \alpha \ E \qquad v_{n\text{-}drift} \ \alpha \ E$$

$$v_{p\text{-}drift} = \mu_p E$$

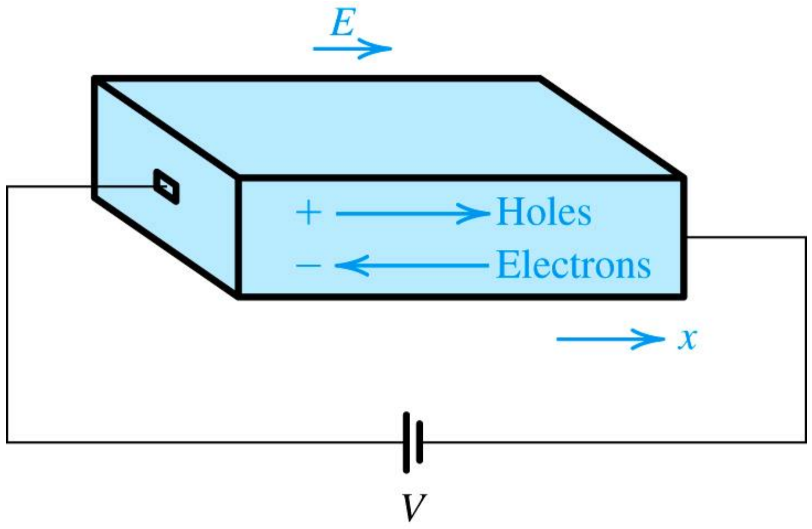
$$v_{n\text{-}drift} = -\mu_n E$$



Drift Current

$$v_{p-drift} = \mu_p E \qquad v_{n-drift} = -\mu_n E$$

- constant of proportionality is the mobility, μ
- v_n and v_p - electron and hole velocity (cm/s)
- μ_n and μ_p - electron and hole mobility ($cm^2/V\cdot s$)
- μ_n ≈ **1350** ($cm^2/V\cdot s$), μ_p ≈ **500** ($cm^2/V\cdot s$)

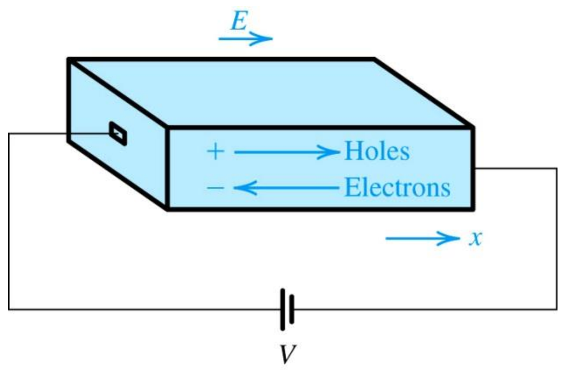


Drift Current

- Assume single-crystal silicon bar, the concentration of holes is defined as p and electrons as n.
- current component attributed to the flow of holes

I_p = current flow attributed to holes
A = cross-sectional area of silicon
q = magnitude of the electron charge
p = concentration of holes
$v_{p-drift}$ = drift velocity of holes

$$I_p = Aqpv_{p-drift}$$



Drift Current

- Substitute in $\mu_p E$

I_p= current flow attributed to holes
A= cross-sectional area of silicon
q= magnitude of the electron charge
p= concentration of holes
μ_p= hole mobility
E= electric field

$$I_p = Aqp\mu_p E$$

- current density as current per unit cross-sectional area $J_p = I_p / A$.

$$J_p = qp\mu_p E$$

Drift Current

- Current component attributed to the flow of electrons

I_n = current flow attributed to electrons
A = cross-sectional area of silicon
q = magnitude of the electron charge
n = concentration of free electrons
μ_n = electron mobility
E = electric field

$$I_n = -Aqnv_{n-drift}$$

$$J_n = qn\mu_n E$$

- Total drift current defined

$$J = J_p + J_n = \underbrace{q(p\mu_p + n\mu_n)}_{\text{this is conductivity } (\sigma)} E$$

Drift Current

- **conductivity** (σ) – relates current density (*J*) and electrical field (*E*)

$$J = \sigma E$$

$$\sigma = q(p\mu_p + n\mu_n)$$

- **resistivity** (ρ) – relates current density (*J*) and electrical field (*E*)

$$J = E / \rho$$

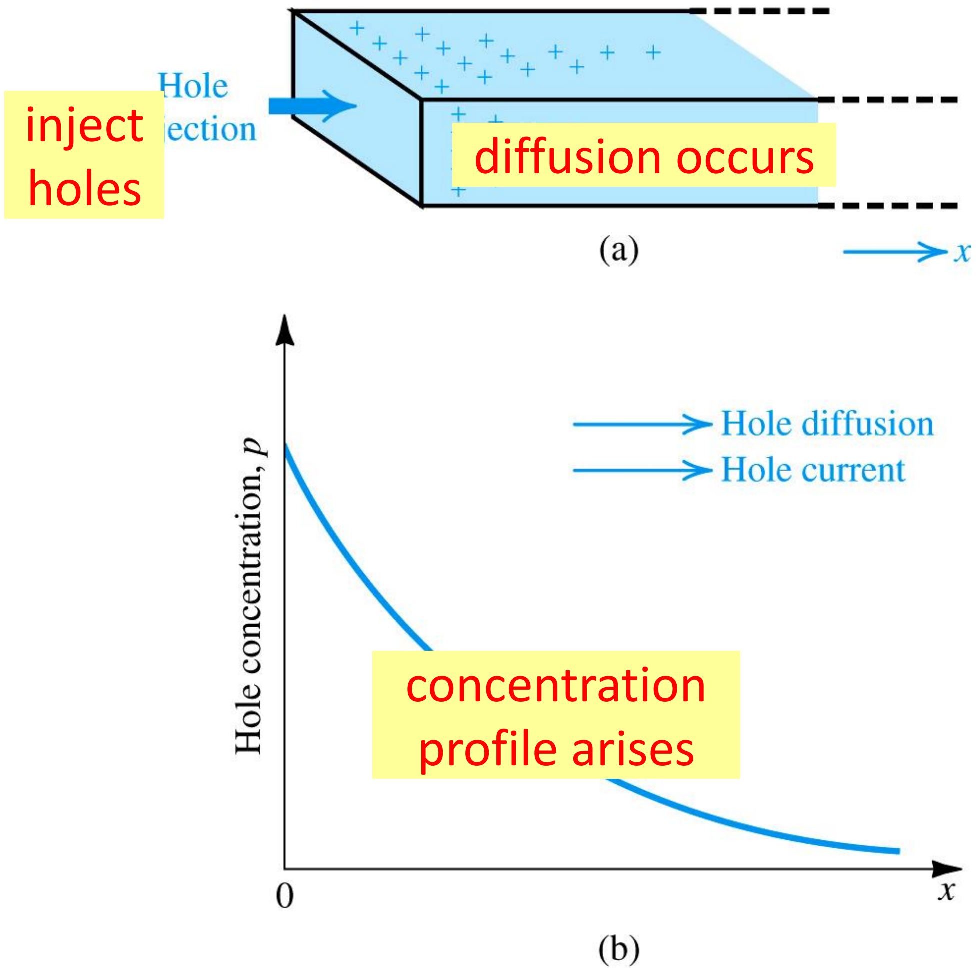
$$\rho = \frac{1}{q(p\mu_p + n\mu_n)}$$

Diffusion Current

- **Carrier diffusion** – is the flow of charge carriers from area of high concentration to low concentration.
  - It requires non-uniform distribution of carriers.
- **Diffusion current** – is the current flow that results from diffusion.

Diffusion Current

- **inject holes** – By some unspecified process, one injects holes in to the left side of a silicon bar.
- **concentration profile arises** – Because of this continuous hole inject, a concentration profile arises.
- **diffusion occurs** – Because of this concentration gradient, holes will flow from left to right.



Diffusion Current

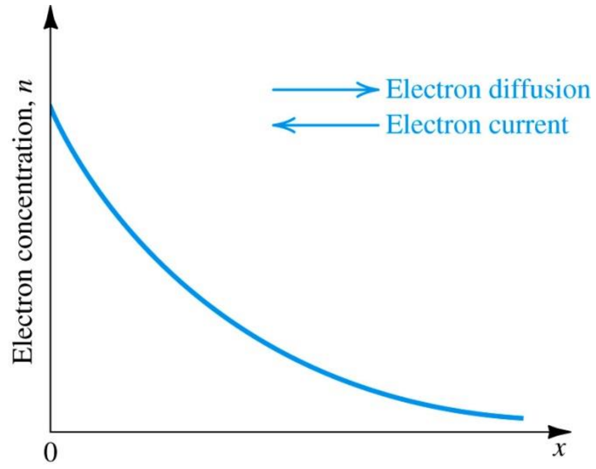
- diffusion current defined by

J_p = current flow density attributed to holes
q= magnitude of the electron charge
D_p = diffusion constant of holes (12cm^2/s for silicon)
p(x)= hole concentration at point x
dp / dx= gradient of hole concentration

hole diffusion current density : $J_p = -qD_p \dfrac{d\mathbf{p}(x)}{dx}$

electron diffusion current density : $J_n = qD_n \dfrac{d\mathbf{n}(x)}{dx}$

J_n = current flow density attributed to free electrons
D_n = diffusion constant of electrons (35cm^2/s for silicon)
n(x)= free electron concentration at point x
dn / dx= gradient of free electron concentration



Diffusion Current

- the relationship between diffusion constant (D) and mobility (μ)
  - **thermal voltage** (V_T)
  - at $T = 300K$, $V_T = 25.9mV$

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T$$

known as Einstein Relationship

Current in Semiconductors

- drift current density (J_{drift})
  - effected by – an electric field (E).

- diffusion current density (J_{diff})
  - effected by – concentration gradient in free electrons and holes.

- Total current is the sum of drift and diffusion current:

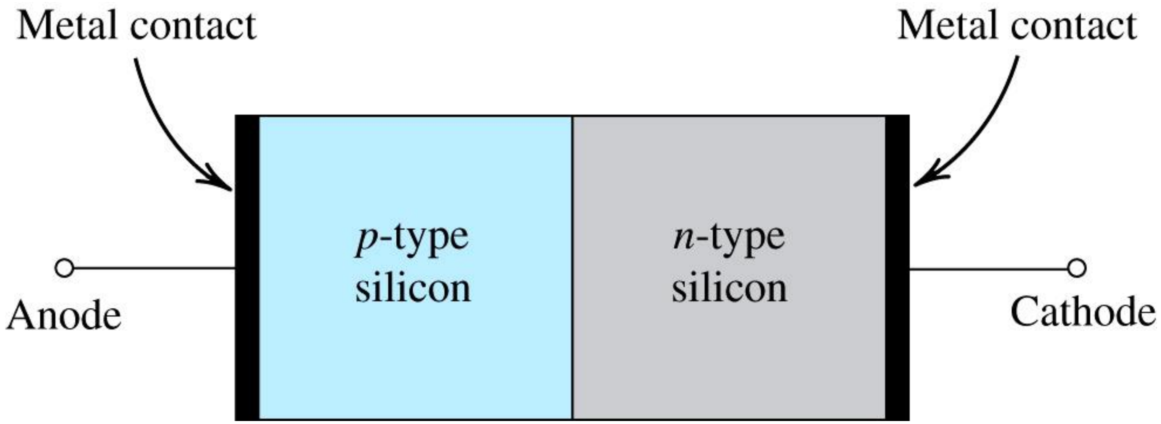
$$j_n^T = q\mu_n nE + qD_n \frac{\partial n}{\partial x}$$

$$j_p^T = q\mu_p pE - qD_p \frac{\partial p}{\partial x}$$

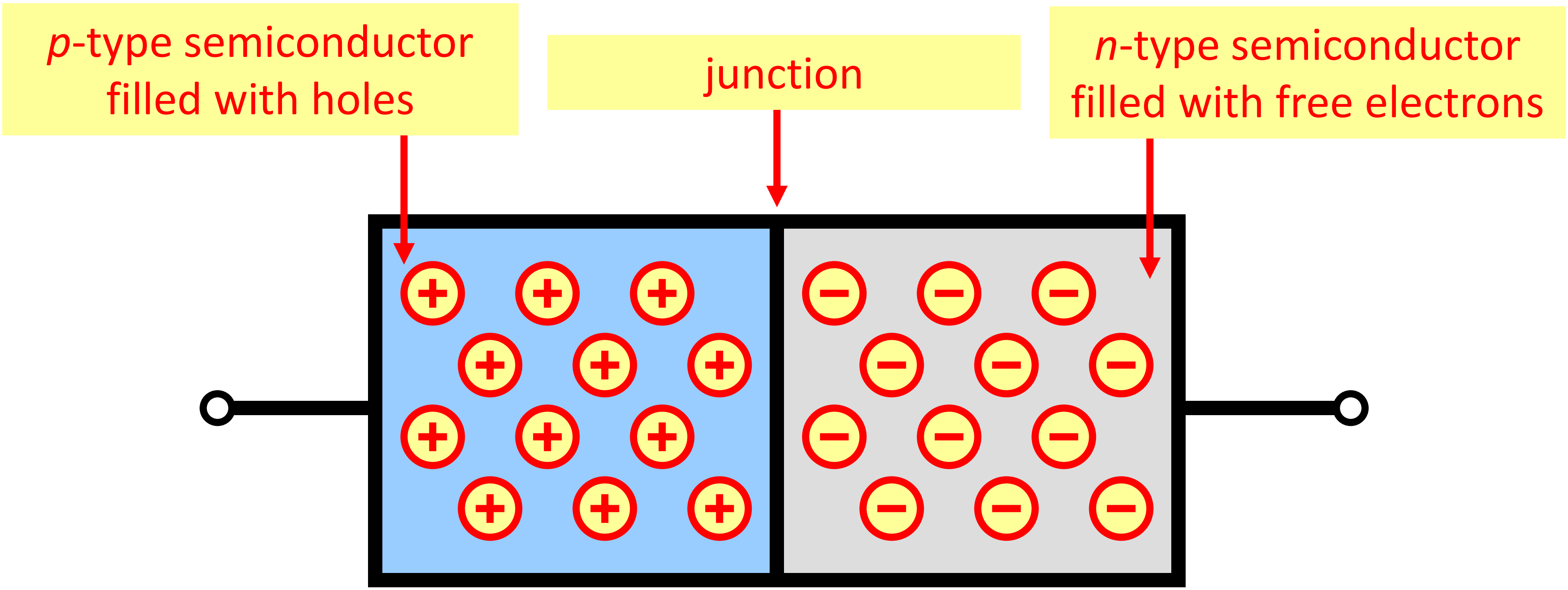
PN junction

PN Junction

- *pn* junction structure
  - p-type semiconductor
  - n-type semiconductor
  - metal contact for connection
- *pn* junction implements the junction diode - terminals are labeled anode and cathode



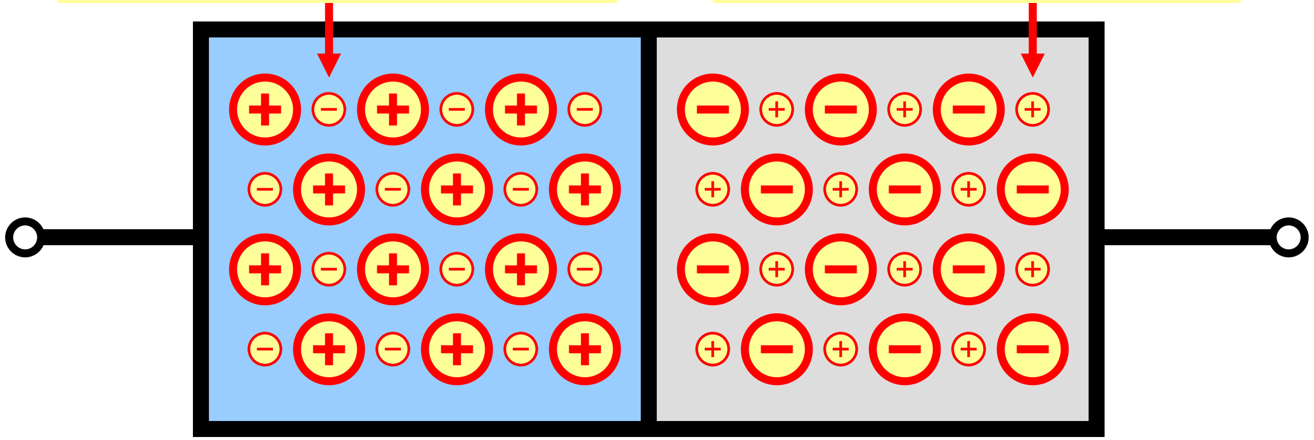
Unbiased PN junction



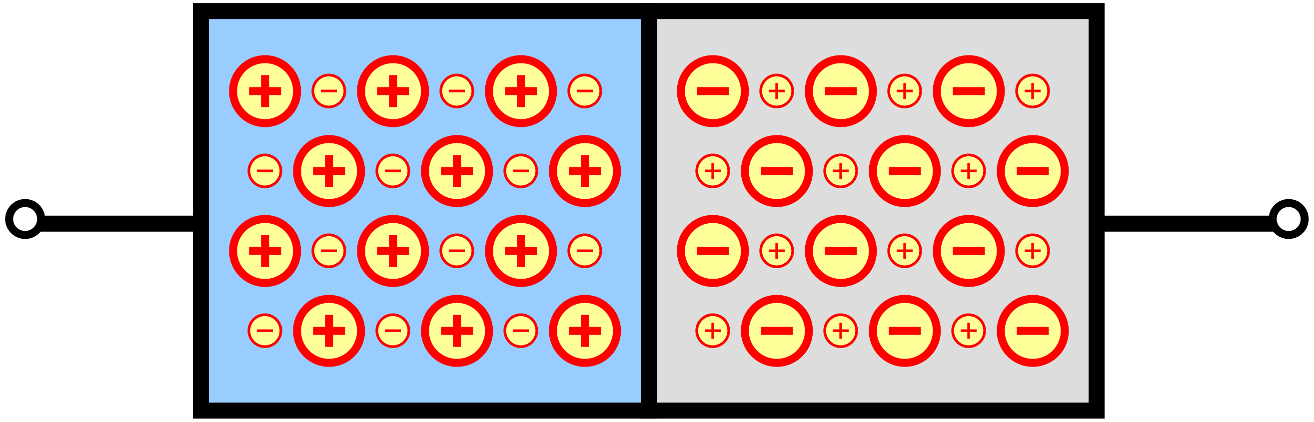
Unbiased PN junction

Small circled minus represent the trivalent atom

Small circled plus represent the pentavalent atom

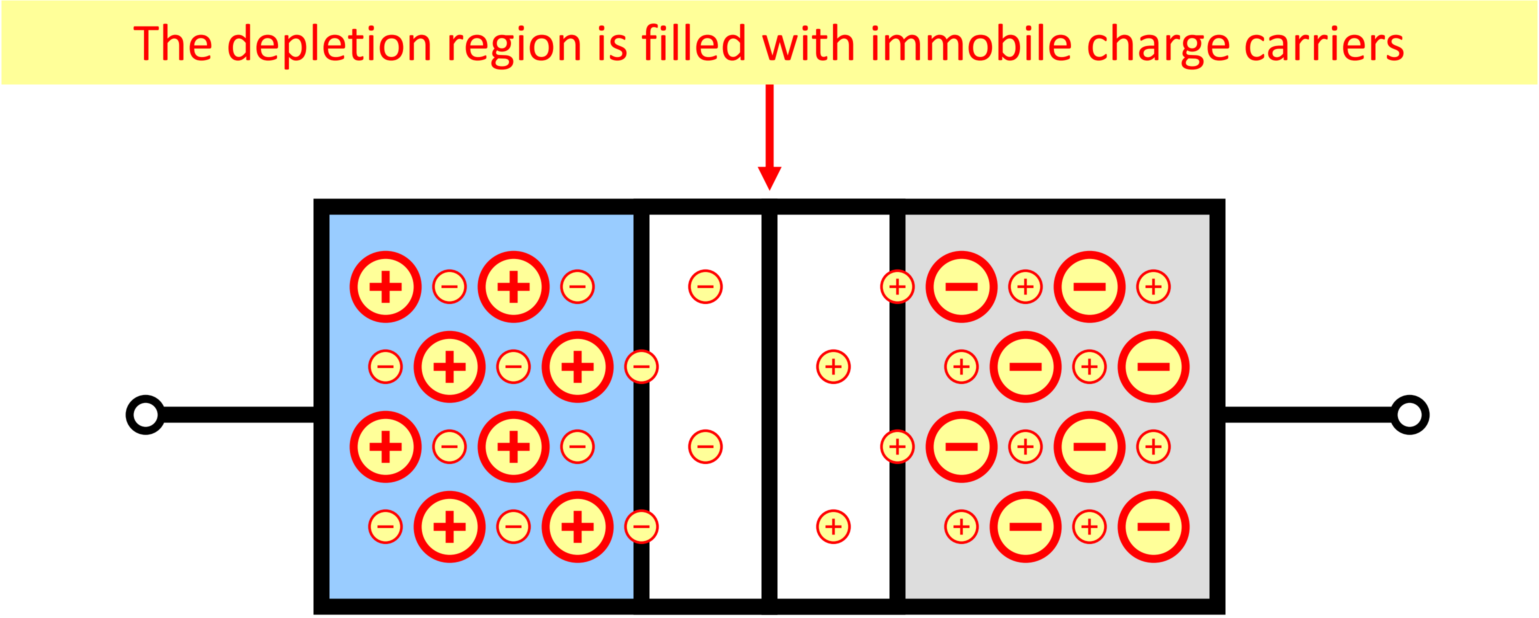


Unbiased PN junction



- Diffusion begins - Those free electrons and holes which are closest to the junction will recombine and, essentially, eliminate one another.

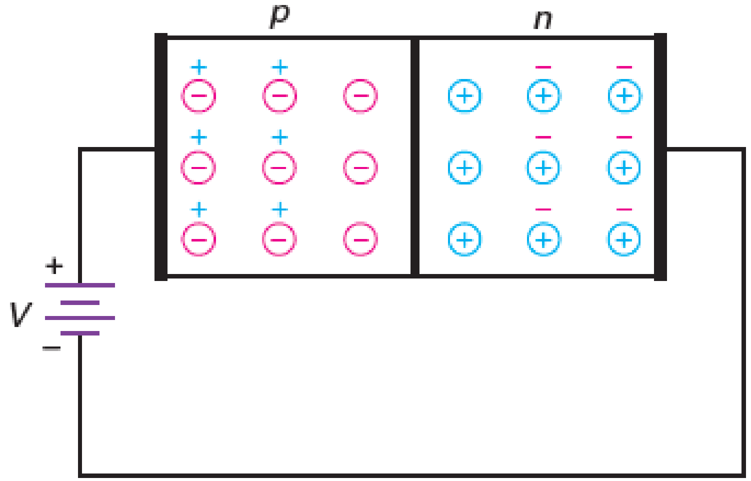
Unbiased PN junction



- The depletion region begins to form – as diffusion occurs and free electrons recombine with holes.
- The electric field between the ions is equivalent to a difference of potential called the barrier potential.
- At 25°C, the barrier potential equals approximately 0.3 V for germanium diodes and 0.7 V for silicon diodes.

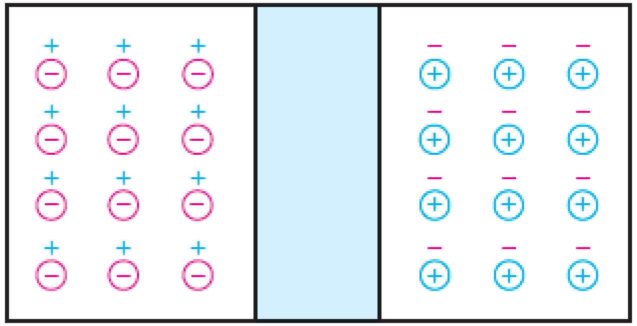
Forward biased Diode

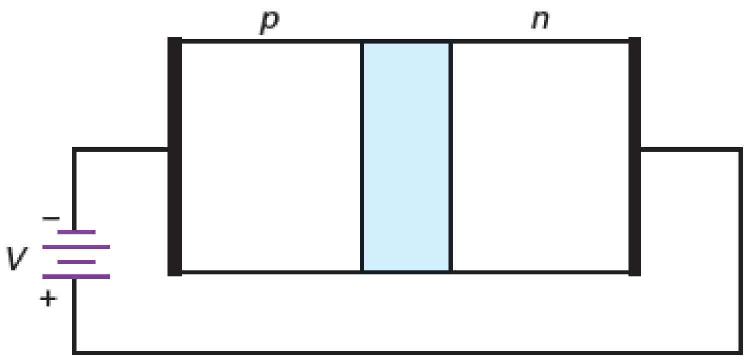
- When the applied voltage is greater than 0.7 V, the free electron has enough energy to get across the depletion layer.
- Soon after the free electron has entered the p region, it recombines with a hole.
- Current flows in a forward-biased diode.
- As long as the applied voltage is greater than the barrier potential, there will be a large continuous current in the circuit



Reverse biased Diode

- Negative terminal attracts the holes, and the positive terminal attracts the free electrons.
- Holes and free electrons flow away from the junction
- Depletion layer gets wider.
- The reverse current caused by the thermally produced minority carriers is called the saturation current.





Effect of biasing in PN junction diode