Drift and Diffusion Currents

- **Current**
  Generated by the movement of charged particles (negatively charged electrons and positively charged holes).

- **Carriers**
  The charged electrons and holes are referred to as **carriers**

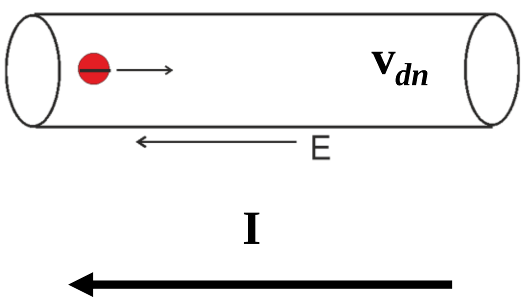
- The two basic processes which cause electrons and holes move in a semiconductor:

  - Drift - the movement caused by electric field.
  - Diffusion - the flow caused by variations in the concentration.

Drift Currents

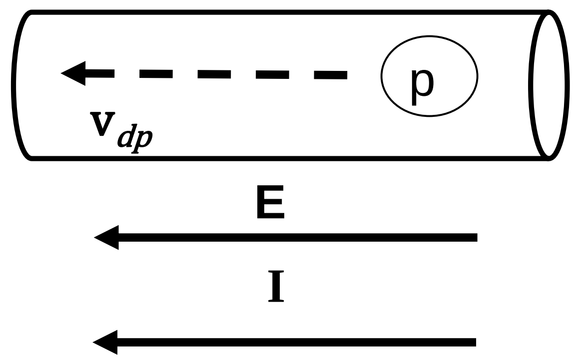
- **Drift Current Density**
  - When an electric field E is applied to a semiconductor, it will produce a force that causes the carriers to move

N-type



- Produces a force on the electrons in the **opposite** direction of the Electric Field, because of the electrons' negative charge.
- The electrons acquire a drift velocity, v_{dn} (in cm/s):

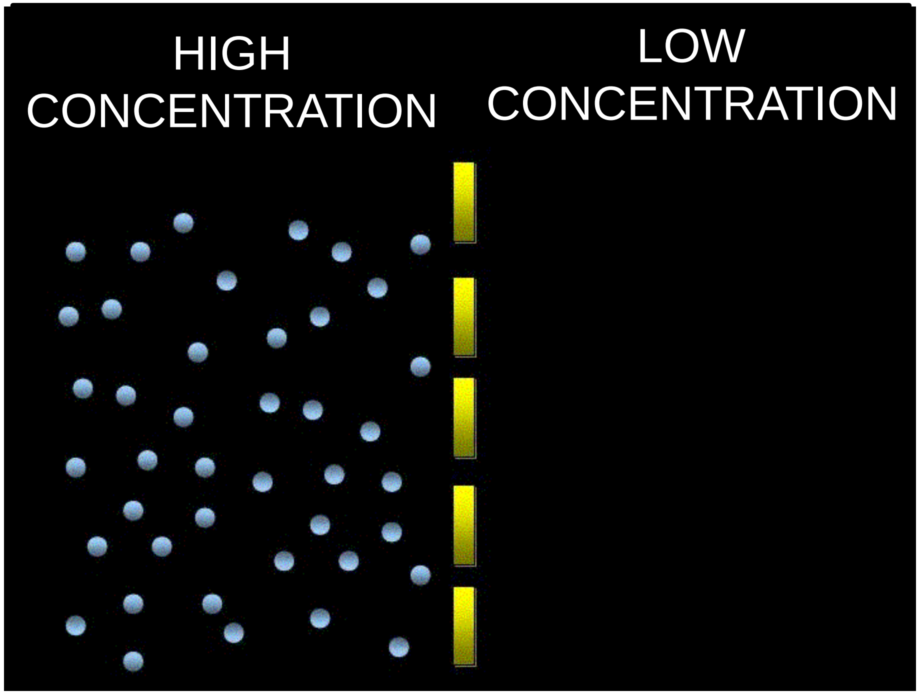
P-type



- Produces a force on the holes in the **same** direction of the Electric Field, because of the positive charge on the holes.
- The holes acquire a drift velocity, v_{dp} (in cm/s):

Diffusion Current

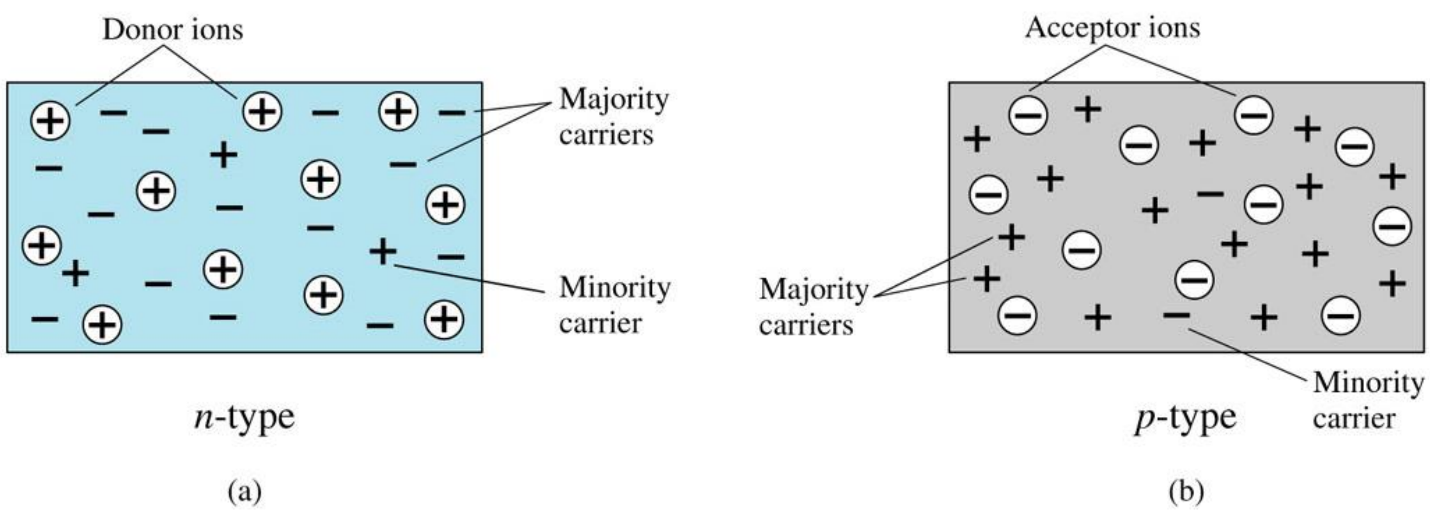
- **The basic diffusion process**
  - Flow of particles from a region of high-concentration to a region of low-concentration.
  - The movement of the particles will then generate the diffusion current



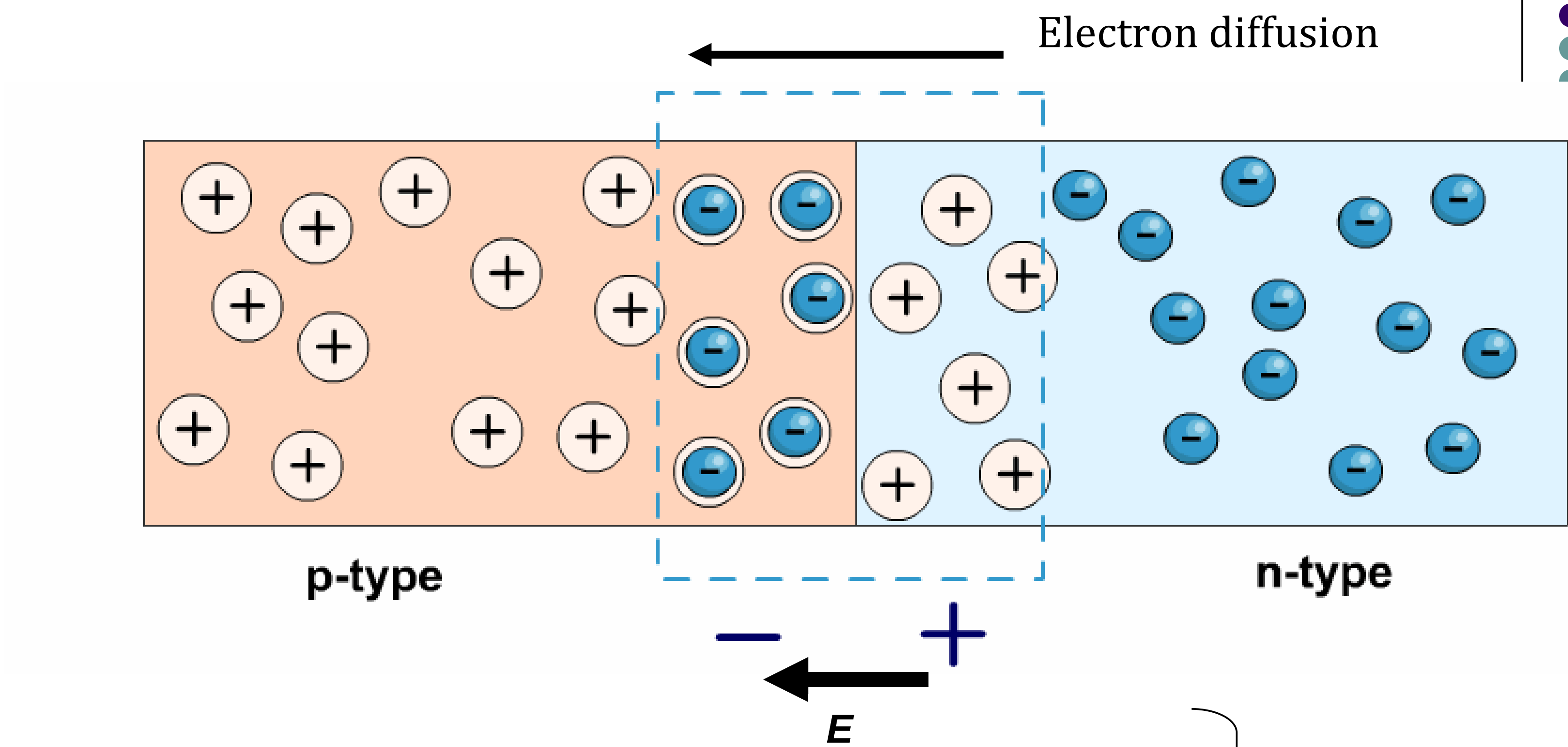
The PN Junction

n-type versus p-type

- In n-type - the electrons are the majority carriers and holes are the minority carriers.
- In p-type - the holes are called the majority carriers and electrons are the minority carriers.



The Equilibrium pn Junction

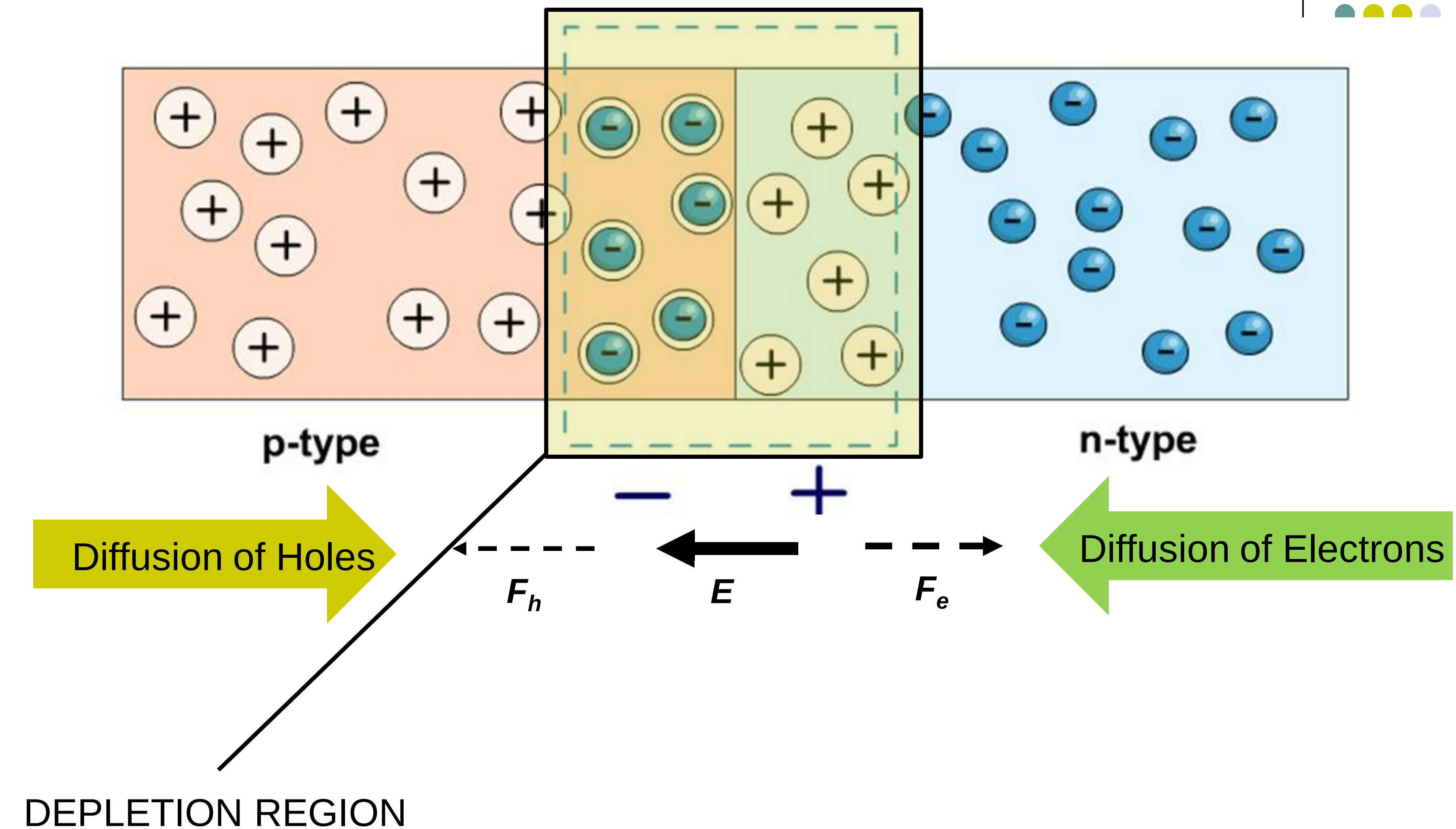


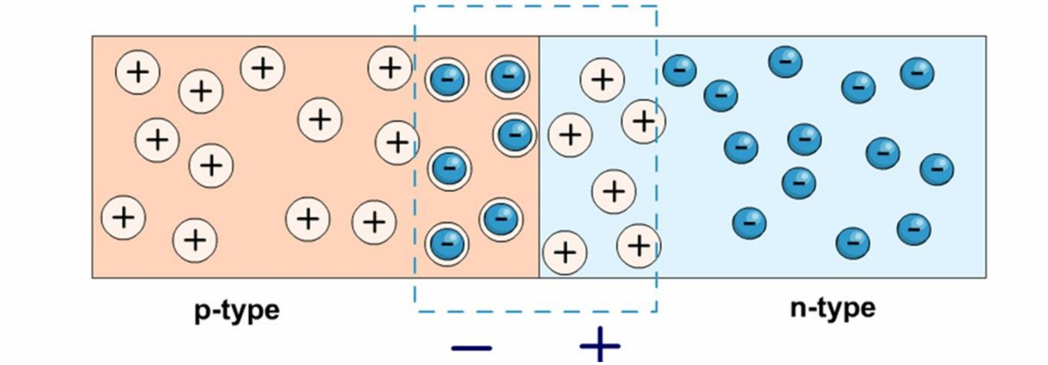
Positive and negative ions are formed by gaining or losing electrons.

- **positively** charged **ions** by losing electrons
- **negatively** charged **ions** by gaining electrons.

Creates a charge separation that produces an electric field, E

The Electric field will create a force that will stop the diffusion of carriers → reaches thermal equilibrium condition





Known as space charge region/depletion region.

Potential difference across the depletion region is called the built-in potential barrier, or built-in voltage:

$$V_{bi} = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right) = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

V_T = thermal voltage = kT/e
k = Boltzmann's constant = 86 x 10^{-6} eV/K = 1.38×10^{-23} J/K
T = absolute temperature
e = the magnitude of the electron charge = 1.6 x 10^{-19} C
N_a = the net acceptor concentration in the p-region
N_d = the net donor concentration in the n-region

NOTE: V_T = **thermal voltage**, $[V_T = kT / e]$ it is approximately **0.026 V at temp, T = 300 K**

The Equilibrium pn Junction

Example 1

Calculate the built-in potential barrier of a pn junction. Consider a silicon pn junction at $T = 300$ K, doped $N_a = 10^{16}$ cm^{-3} in the p-region, $N_d = 10^{17}$ cm^{-3} in the n-region and $n_i = 1.5 \times 10^{10}$ cm^{-3}.

Solution

$$V_{bi} = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right) = (0.026)\ln\left[\frac{(10^{16})(10^{17})}{(1.5 \times 10^{10})^2}\right] = 0.757\ \text{V}$$

$$V_{bi} = \frac{kT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right) = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

- Example 2

Consider a silicon pn junction at T = 400K, doped with concentrations of $N_d = 10^{18}$ cm^{-3} in n-region and $N_a = 10^{19}$ cm^{-3} in p-region. Calculate the built-in voltage V_{bi} of the pn junction, given B and Eg for silicon are 5.23 x 10^{15} cm^{-3} $K^{-3/2}$ and 1.1 eV respectively

Consider a silicon pn junction at T = 400K, doped with concentrations of $N_d = 10^{18}$ cm^{-3} in n-region and $N_a = 10^{19}$ cm^{-3} in p-region. Calculate the built-in voltage V_{bi} of the pn junction, given B and Eg for silicon are 5.23 x 10^{15} cm^{-3} K$^{-3/2}$ and 1.1 eV respectively

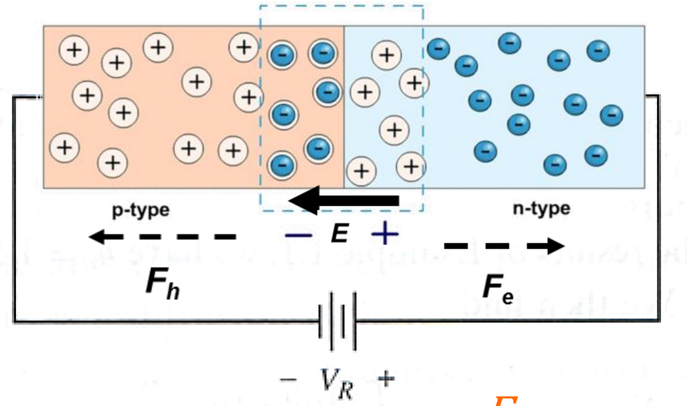
- Calculation of V_T =
  =

- Calculation of $n_i = BT^{3/2} \exp(-Eg / 2kT)$

- Calculation of $V_{bi} = V_T \ln(N_a N_d / n_i^{2})$

Reverse-Biased pn Junction

- +ve terminal is applied to the n-region of the pn junction and vice versa.

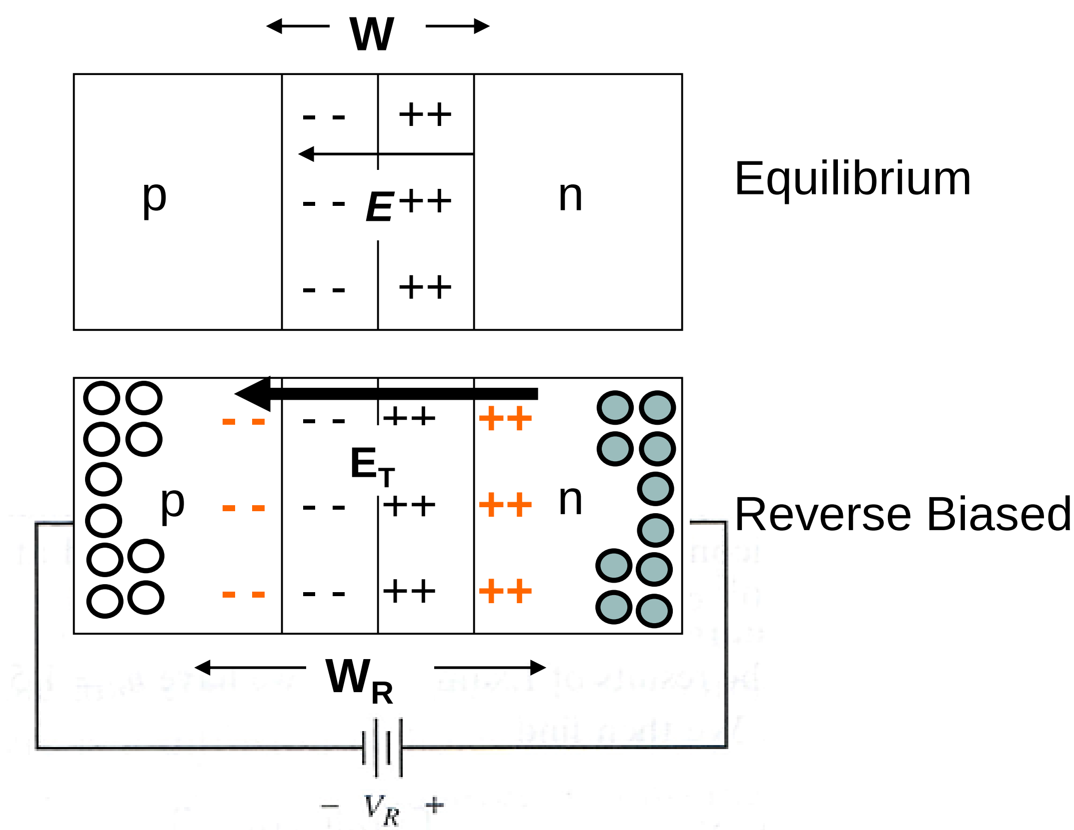


E

- Applied voltage V_R will induce an applied electric field E_A.
- Direction of the E_A is the same as that of the E-field in the space-charge region.
- Magnitude of the electric field in the space-charge region increases above the thermal equilibrium value. Total $E_T = E + E_A$
- Increased electric field holds back the holes in the p-region and the electrons in the n-region.
- Hence, no current will flow through the pn junction except for a very small reverse bias current that can be neglected

Reverse-Biased pn Junction

- The depletion region is wider during reverse biased
- The negative terminal of the power supply attracts the holes from the p-region and the positive terminal attract the electrons from p-region.
- So, the majority charge carriers move away from the junction. This increases the width of the depletion layer.



The space charge region/depletion region increase with increase of reverse-bias voltage, so a capacitor is associated with the pn junction when a reverse-bias voltage is applied. The junction capacitance or depletion layer capacitance of a pn junction is

$$C_j = C_{j0}\left(1 + \frac{V_R}{V_{bi}}\right)^{-1/2}$$

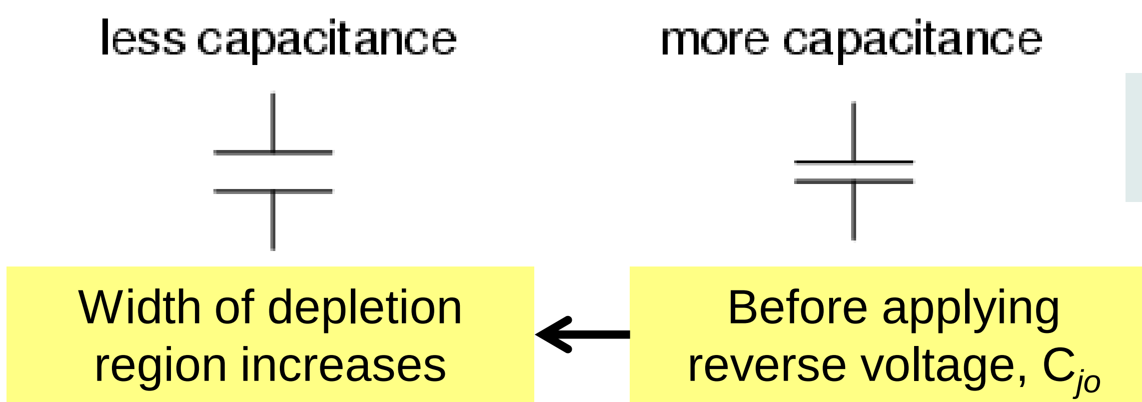
EXAMPLE 2.4 Calculate the junction capacitance of a silicon pn junction diode. Consider that the diode is at room temperature (T = 300°K), with doping concentrations of $N_a = 1.5 \times 10^{16}$ cm^{-3} , $N_d = 1.0 \times 10^{15}$ cm^{-3} and let $C_{j0} = 1.5$ pF Calculate the junction capacitance at reverse bias 3.5 V.

$$V_{bi} = \frac{kT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right) = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$V_b = (0.026) \ln\left[\frac{(1.5 \times 10^{16})(1.0 \times 10^{15})}{(1.5\times10^{10})^2}\right] = 0.6479 \text{ V}$$

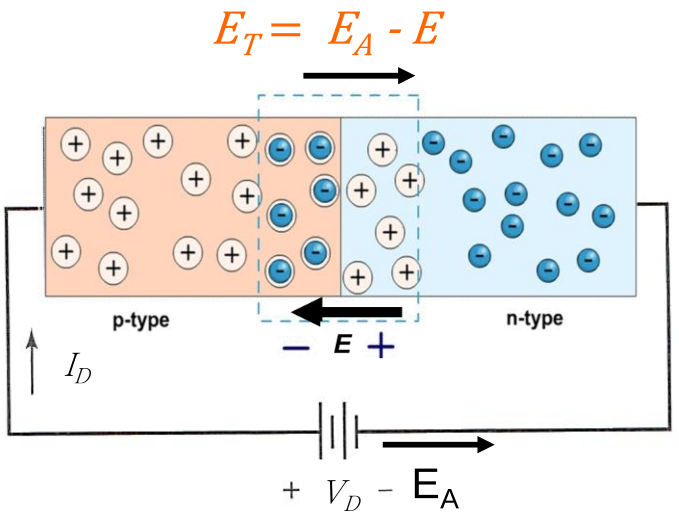
The junction capacitance at $V_R = 3.5$ V is

$$C_j = C_{j0}\left(1 + \frac{V_R}{V_b}\right)^{-1/2} = (1.5)\left(1 + \frac{3.5}{0.6479}\right)^{-1/2} = 0.5928 \text{ pF}$$



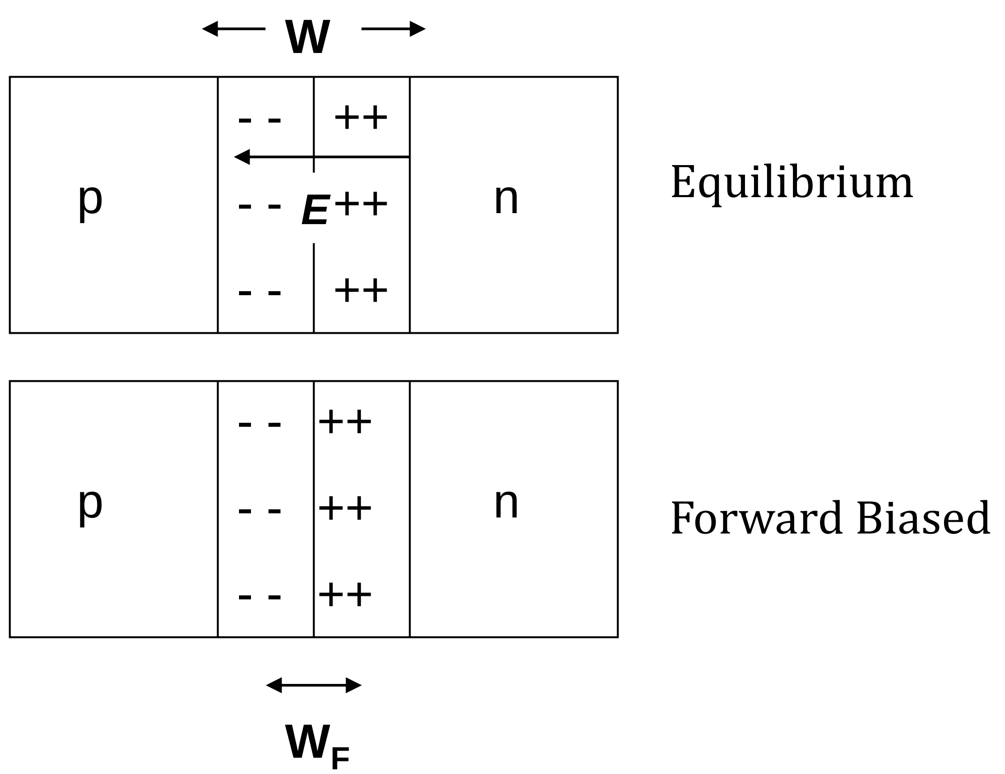
$$C = \frac{\varepsilon A}{d}$$

Forward-Biased pn Junction



- +ve terminal is applied to the p-region of the pn junction and vice versa.
- Direction of the applied electric field E_A is the opposite as that of the E-field in the space-charge region.
- The net result is that the electric field in the space-charge region lower than the thermal equilibrium value causing diffusion of charges to begin again.
- The diffusion process continues as long as V_D is applied.
- Creating current in the pn junction, I_D

Forward-Biased pn Junction



Due to the diffusion of carriers→ the width of the depletion region reduces

Ideal Current-Voltage Relationship

Current I_D equation of a pn junction diode:

$$I_D = I_S \left[e^{\left(\frac{V_D}{n\,V_T}\right)} - 1 \right]$$

I_S = the reverse-bias saturation current (for silicon 10^{-15} to 10^{-13} A)

V_T = the thermal voltage (0.026 V at room temperature)

n = the emission coefficient ($1 \leq n \leq 2$) – normally it is set 1

Ideal Current-Voltage Relationship

Example

Determine the current in a pn junction diode.

Consider a pn junction at $T = 300$ K in which $I_S = 1.4 \times 10^{-14}$ A and $n = 1.1$

Find the diode current for $v_D = +0.75$ V and $v_D = -0.75$ V.

Solution: For $V_D = +0.75$ V, the diode is forward-biased and

$$I_D = I_S\left[e^{\left(\frac{V_D}{n\,V_T}\right)} - 1\right] = (1.4 \times 10^{-14})\left[e^{\left(\frac{0.75}{1.1 \times 0.026}\right)} - 1\right] = 3.427 \text{ mA}$$

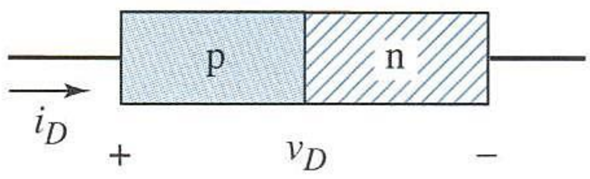
For $V_D = -0.75$ V, diode is reverse-biased and

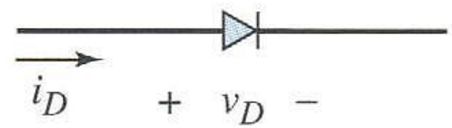
$$I_D = I_S\left[e^{\left(\frac{V_D}{n\,V_T}\right)} - 1\right] = (1.4 \times 10^{-14})\left[e^{\left(\frac{-0.75}{1.1 \times 0.026}\right)} - 1\right] = -1.4 \times 10^{-14} \text{ A}$$

Very small current

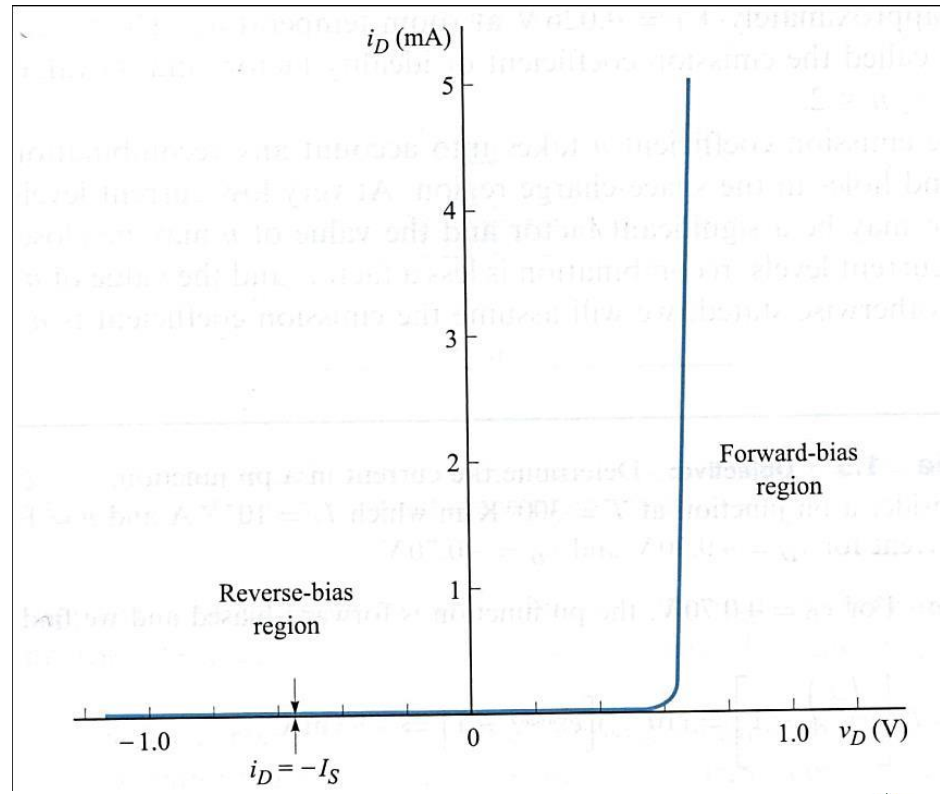
PN Junction Diode

- The basic PN junction diode circuit symbol, and conventional current direction and voltage polarity.





- The graphs shows the ideal I-V characteristics of a PN junction diode.
- The diode current is an exponential function of diode voltage in the forward-bias region.
- The current is very nearly zero in the reverse-bias region.



PN Junction Diode

- Temperature Effects
  - Both I_S and V_T are functions of temperature.
  - The diode characteristics vary with temperature.
  - For silicon diodes, the change is approximately 2 mV/°C.

- Forward-biased PN junction characteristics versus temperature.
- The required diode voltage, $\mathbf{V_\gamma}$ to produce a given current decreases with an increase in temperature.