PN- Junctions

MUHAMMAD HAFEEZ JAVED

rmhjaved@gmail.com

www.rmhjaved.com

Recall-Lecture 2

- Introduction to Electronics
- Atomic structure of Group IV materials particularly on Silicon
- Intrinsic carrier concentration, n_i

$$n_i = BT^{3/2}\, e^{\left(\frac{-E_g}{2kT}\right)}$$

Recall-Lecture 2

- Extrinsic semiconductor
  - N-type – doped with materials from Group V
    - Majority carriers = electron
  - P-type – doped with materials from Group III
    - Majority carriers = holes

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:

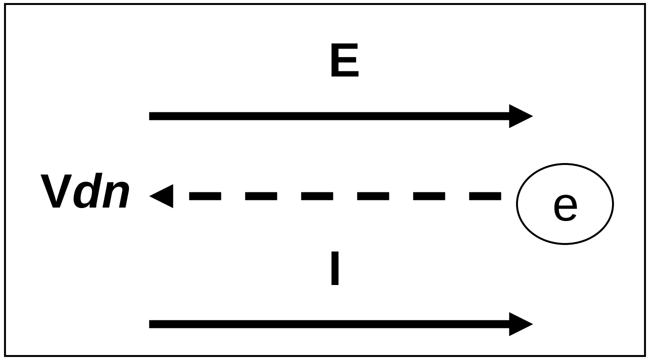
  - **Drift** - the movement caused by electric field.
  - **Diffusion** - the flow caused by variations in the concentration.

Drift Currents

- **Drift Current Density** (n-type semiconductor)
  - An electric field *E* applied to n-type semiconductor with a large number of free electrons.

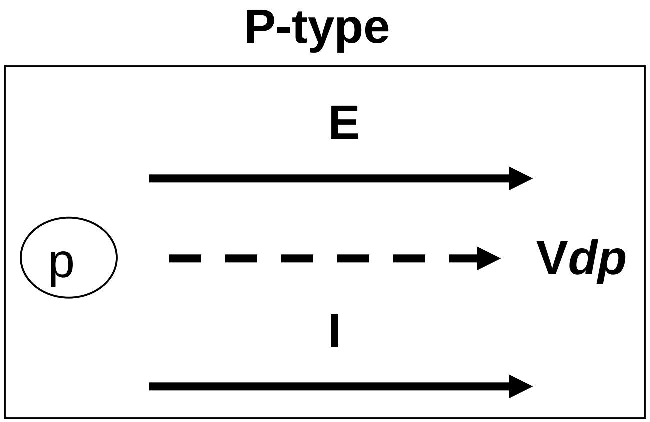
    - **Produces a force on the electrons in the opposite direction, because of the electrons' negative charge.**
    - **The electrons acquire a drift velocity, V_{dn} (in cm/s):**

N-type



Drift Currents

- **Drift Current Density** (p-type semiconductor)
  - An electric field *E* applied to p-type semiconductor with a large number of holes.
    - **Produces a force on the holes in the same direction, because of the positive charge on the holes.**
    - **The holes acquire a drift velocity, V_{dp}(in cm/s):**



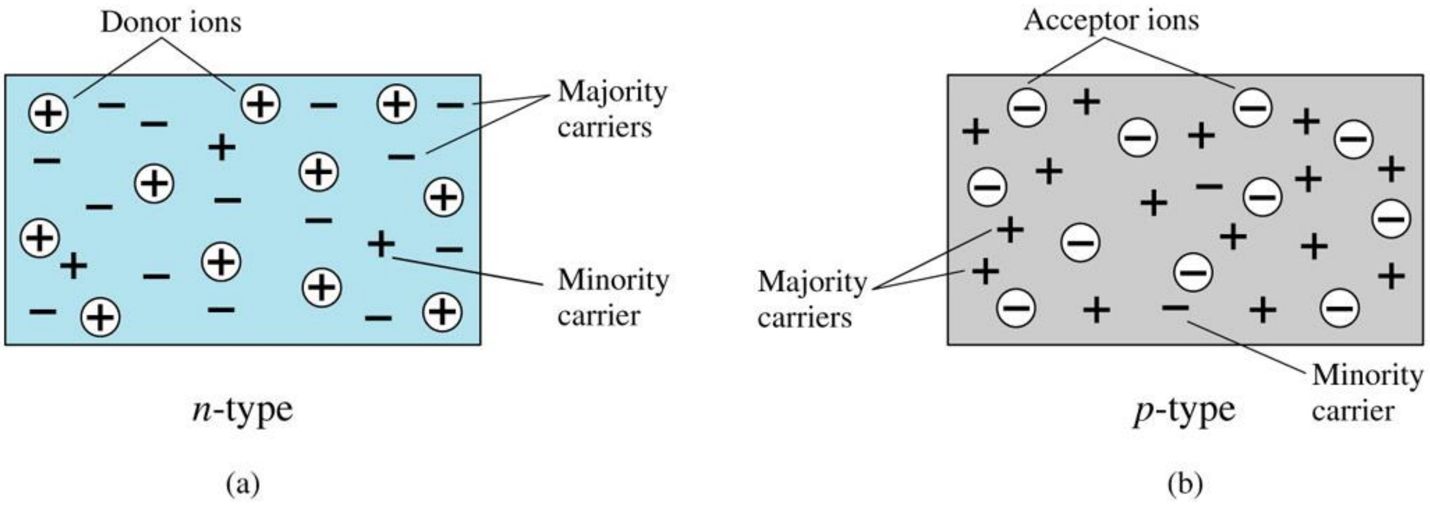
Diffusion Current

- **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

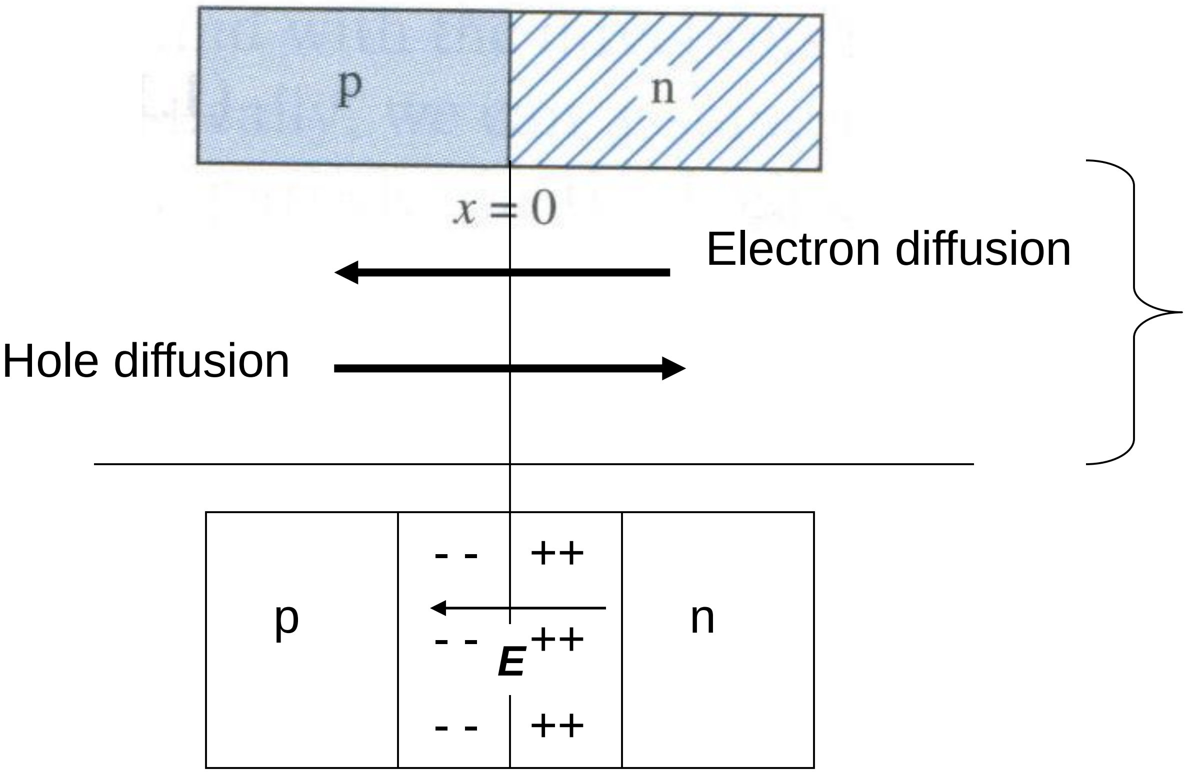
n-type versus p-type

- 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.



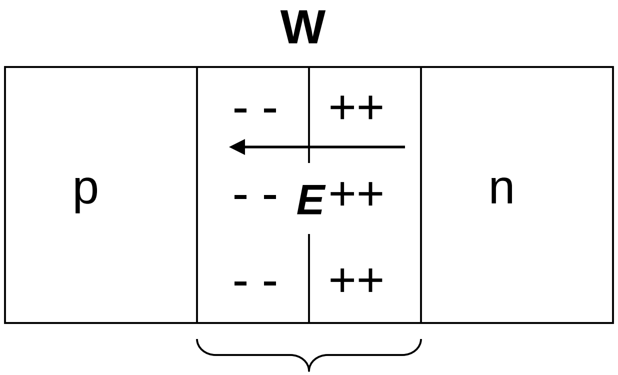
The Equilibrium pn Junction

- Join n-type and p-type doped Silicon (or Germanium) to form a **p-n junction**.



Creates a charge separation that sets up 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 <u>built-in potential</u> barrier, or built-in voltage:

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

$V_T = kT/e$
k = Boltzmann’s constant
T = absolute temperature
e = the magnitude of the electronic charge = 1 eV
N_a = the net acceptor concentration in the p-region
N_d = the net donor concentration in the n-region

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

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

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

- 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 Given B and Eg for silicon are 5.23 x 10^{15} cm^{-3} K$^{-3/2}$ and 1.1 eV respectively

ANSWER

- Calculation of $V_T = kT / e = 86 \times 10^{-6} (400) / 1eV = 0.0344$ V

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

  $= 5.23 \times 10^{15} (400)^{3/2} \exp \left[-1.1 / 2 (86 \times 10^{-6}) (400) \right]$

  $= 4.76 \times 10^{12}$ cm $^{-3}$

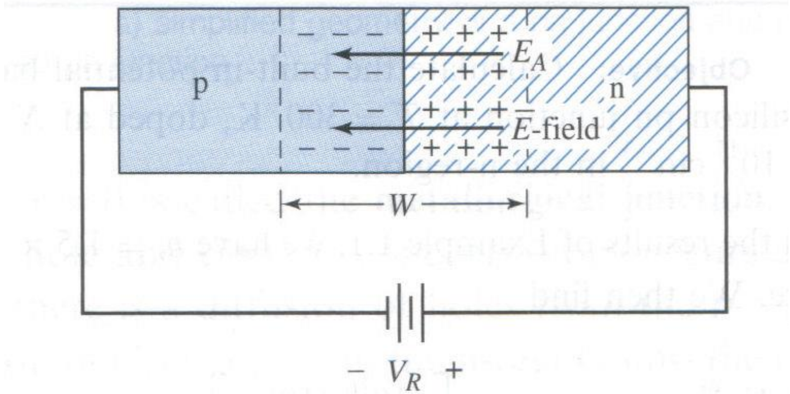
- Calculation of $V_{bi} = V_T \ln (N_a N_d / \left[n_i^{2}) \right]$

  $= 0.0344 \ln 10^{18} (10^{19}) / (4.76 \times 10^{12})^2$

  $= \underline{0.922V}$

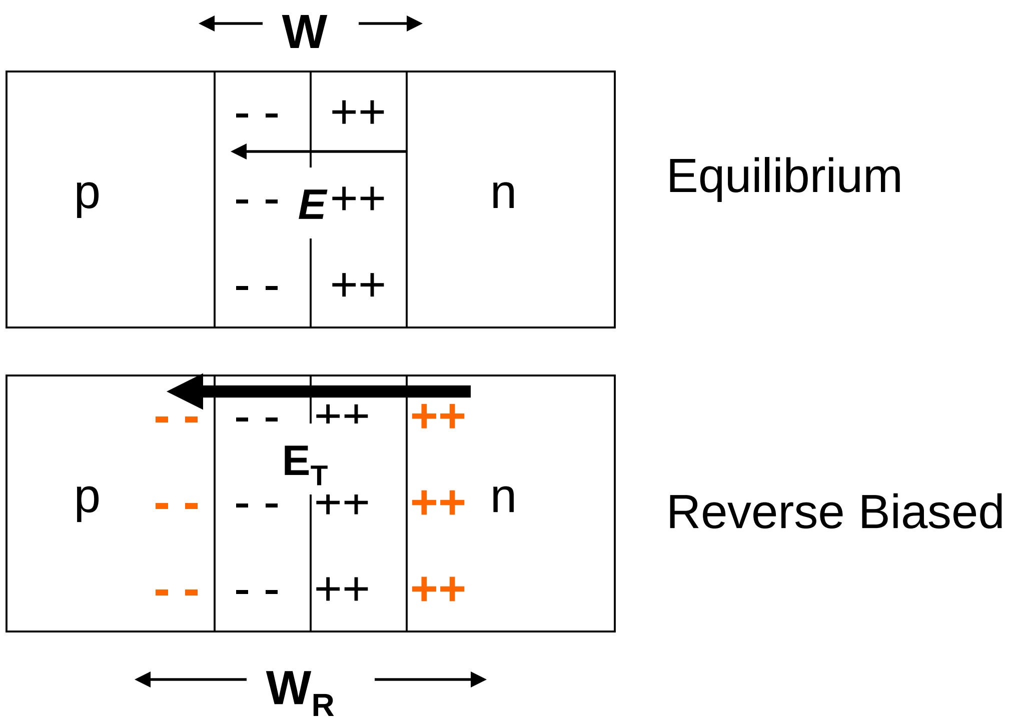
Reverse-Biased pn Junction

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



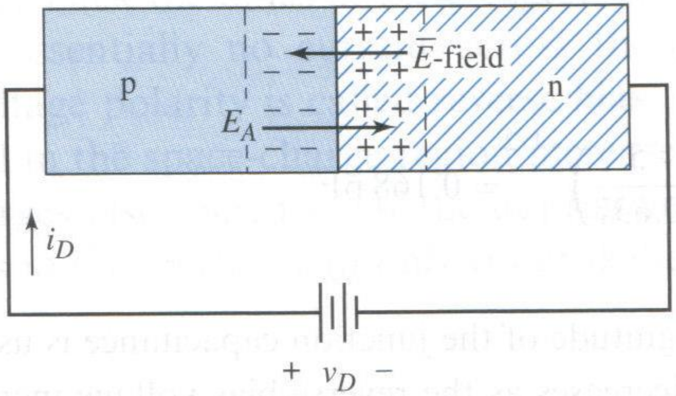
Reverse-Biased pn Junction

- Hence, no current across the pn junction.
- This applied voltage polarity is called **reverse bias**.
- $E \propto \textit{charge}$ so, since there is an increase of the electric field in the depletion region, the number of charges increases too since the width of the depletion increases.

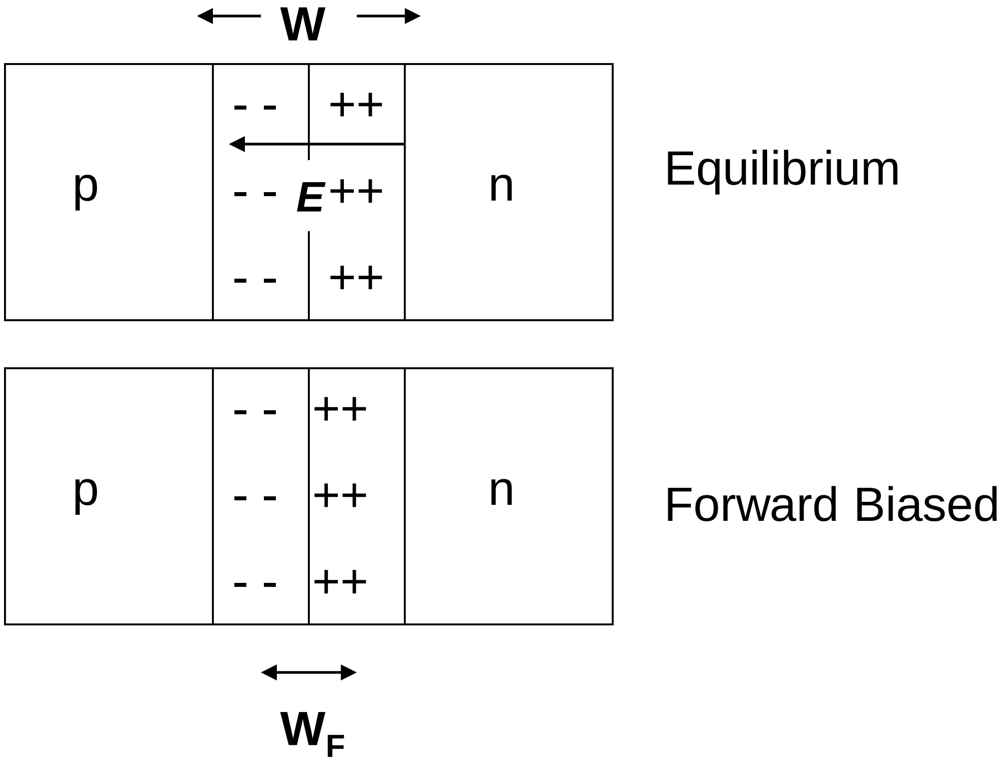


Forward-Biased pn Junction

- +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



Width reduces, causing diffusion of carriers→ current flows

Ideal Current-Voltage Relationship

- So, the current i_D is

$$\boxed{i_D = I_S\left[e^{\left(\frac{v_D}{nV_T}\right)} - 1\right]}$$

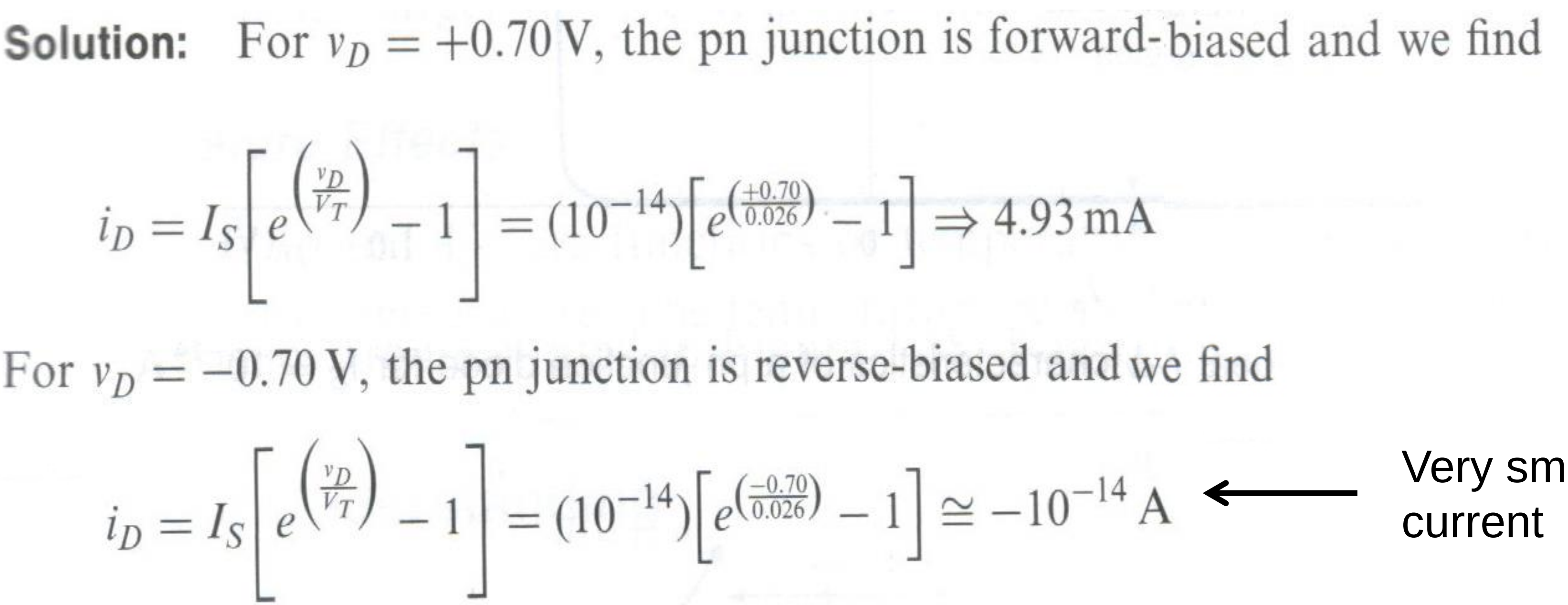
I_S = the reverse-bias saturation current (for silicon 10^{-15} to 10^{-13} A)

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

n = the emission coefficient ($1 \leq n \leq 2$)

Ideal Current-Voltage Relationship

Example
Determine the current in a pn junction diode.
Consider a pn junction at T = 300 K in which $I_S = 10^{-14}$ A and n = 1.
Find the diode current for v_D = +0.70 V and v_D = -0.70 V.



Solution: For $v_D = +0.70\,\text{V}$, the pn junction is forward-biased and we find

$$i_D = I_S\left[e^{\left(\frac{v_D}{V_T}\right)}-1\right] = (10^{-14})\left[e^{\left(\frac{+0.70}{0.026}\right)}-1\right] \Rightarrow 4.93\,\text{mA}$$

For $v_D = -0.70\,\text{V}$, the pn junction is reverse-biased and we find

$$i_D = I_S\left[e^{\left(\frac{v_D}{V_T}\right)}-1\right] = (10^{-14})\left[e^{\left(\frac{-0.70}{0.026}\right)}-1\right] \cong -10^{-14}\,\text{A}$$

Very small current

- **Example 2**
  - A silicon pn junction diode at T=300K has a reverse biased current of $I_s = 10^{-14}$ A. Determine the forward biased current for

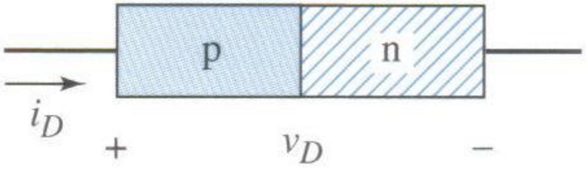
i. $V_D = 0.5V$

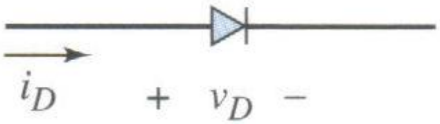
ii. $V_D = 0.6V$

iii. $V_D = 0.7V$

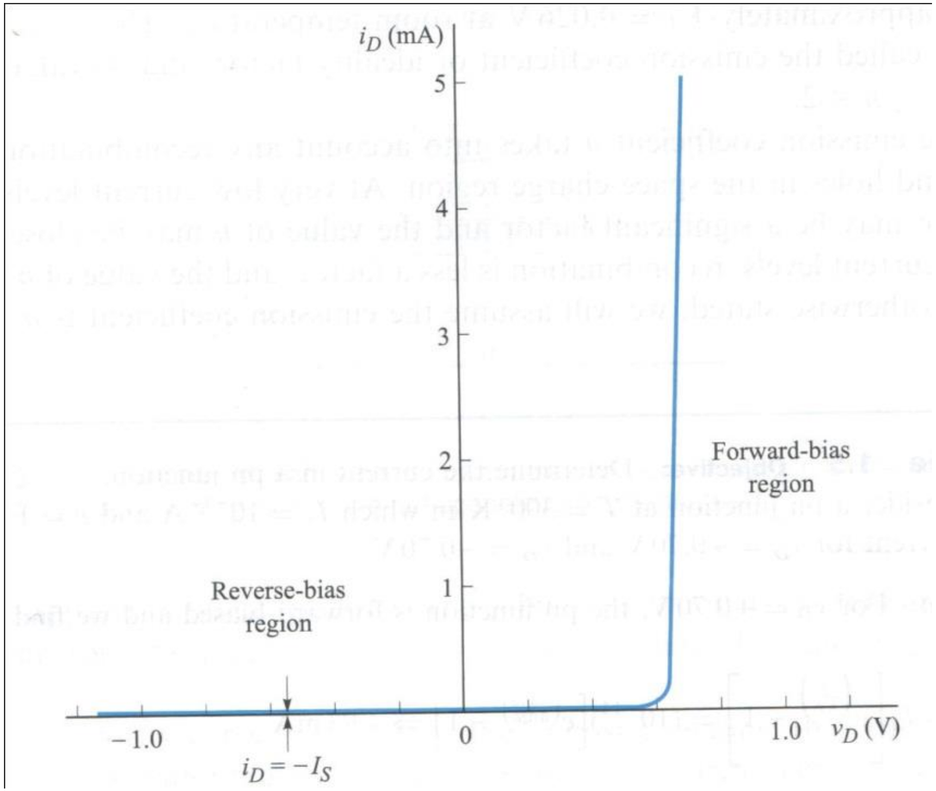
PN Junction Diode

- 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, **V_γ** to produce a given current decreases with an increase in temperature.