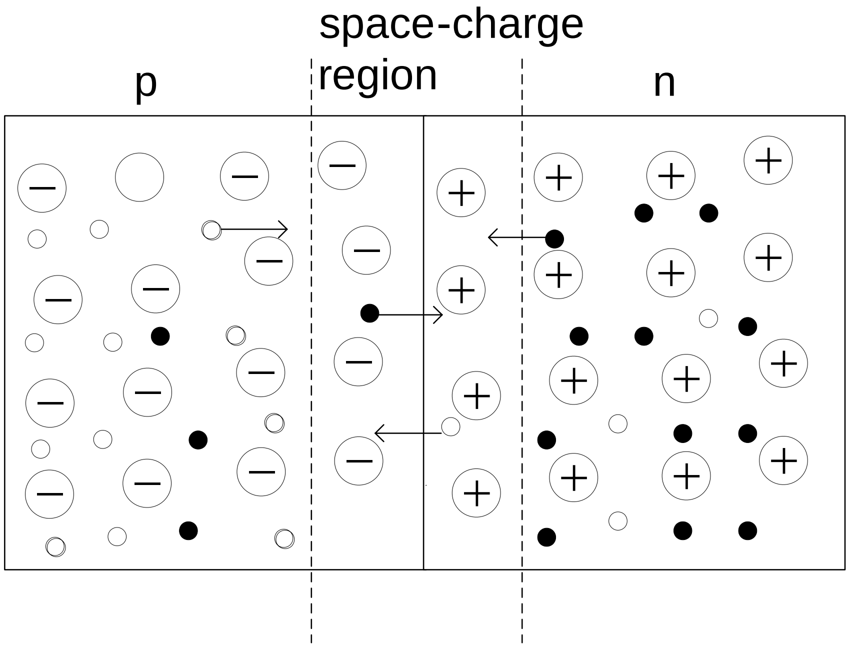
CLASS 6&7

p-n junction biasing, p-n I-V characteristics, p-n currents

p-n junction biasing

- Unbiased p-n junction:

  the potential barrier is 0.7 V for Si and 0.3 V for Ge. Nett current across the p-n junction is 0 since the majority carriers' diffusion current cancels off the minority carriers' drift current

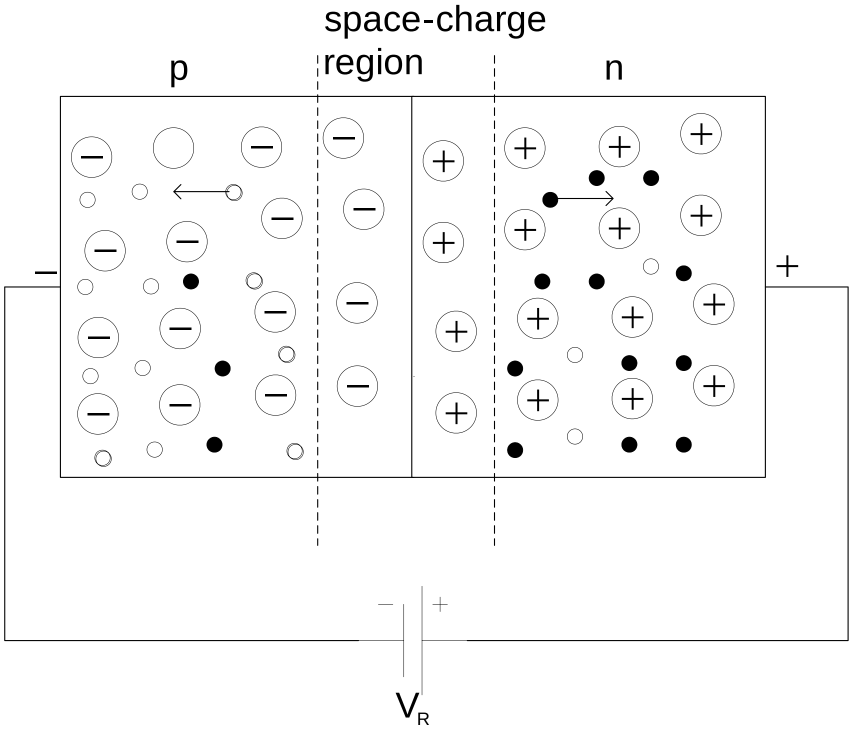


- **Reverse bias**

  Majority carriers moving away from the junction as the holes in p will be attracted to the –ve terminal and electrons in n will be attracted to the +ve terminal of the voltage supply.

  Effects:

1. Depletion region ↑
2. Potential barrier ↑
3. Very difficult for the majority carriers in the p and n to cross the p-n junction. Hence, no diffusion current will be generated.

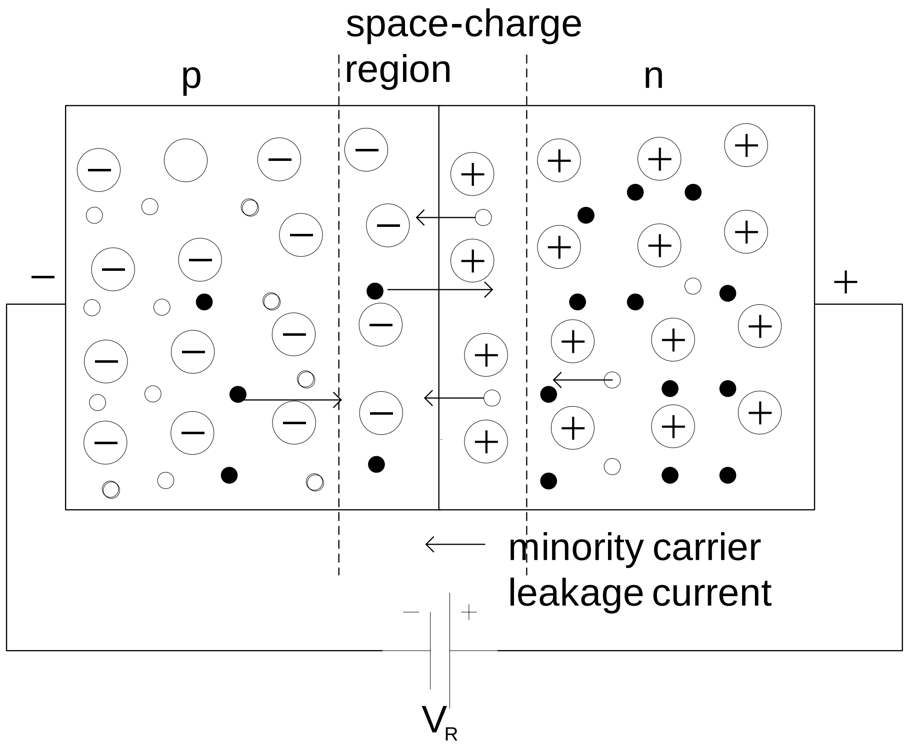


4. Minority carriers will flow across the p-n junction producing <u>reverse leakage current.</u>

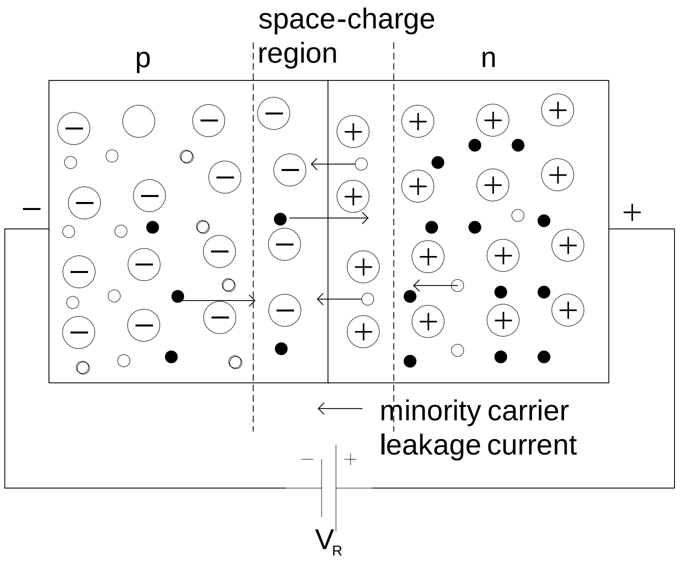
Reasons:

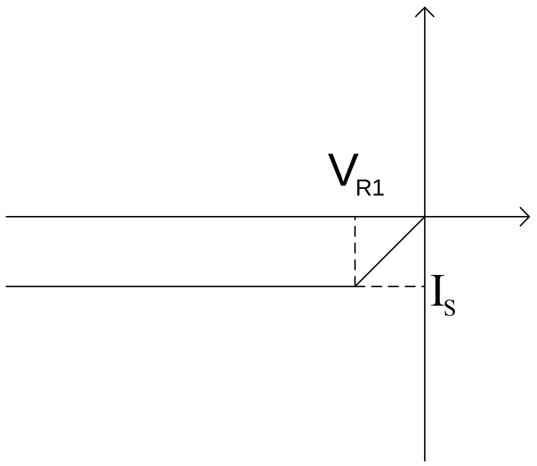
-Electrons in p moving towards the junction away from the -ve terminal. Holes in n moving towards the junction away from the +ve terminal.

-The fixed +ve ions will attract electrons in p space-charge region to cross the junction. The fixed -ve ions will attract holes in n space-charge region to cross the junction.



- Initially, the reverse current will increase when V_R is increased. This is because more minority carriers are able to cross the p-n junction. Beyond V_{R1}, current will be constant at I_S. This is because, if the temperature does not increase, the number of minority carriers will be quite consistent. Minority carriers will increase with the increase in temperature.
- I_S is called reverse saturation current. I_S for Ge is in µA and for Si is in nA. This is because the bandgap for Ge < than the bandgap for Si. Hence, at the same temperature, electron-hole pairs in Ge > than the electron-hole pairs in Si.





- Reverse breakdown in p-n junction

  Breakdown voltage = V_{BD}

  If $V_R > V_{BD}$, the reverse current I_R will increase tremendously with just a small increase in V_R. This is the reverse breakdown condition.

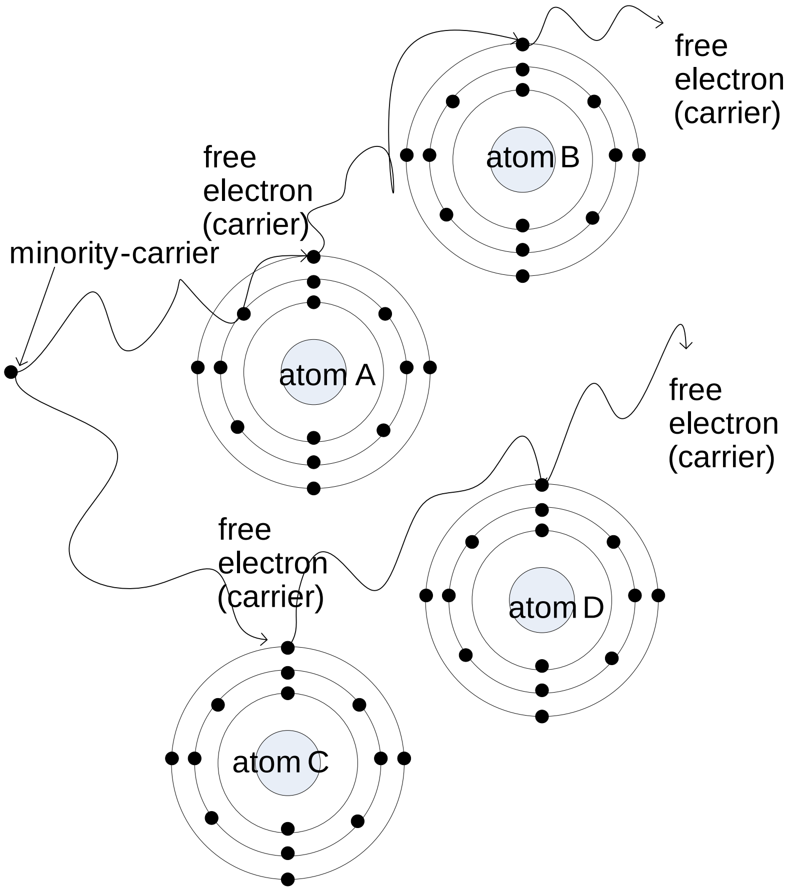
  Under the reverse breakdown condition, the reverse current is large and may damage the p-n junction if not limited by a series resistor. Hence, reverse breakdown is an unwanted condition

- How does breakdown occur?

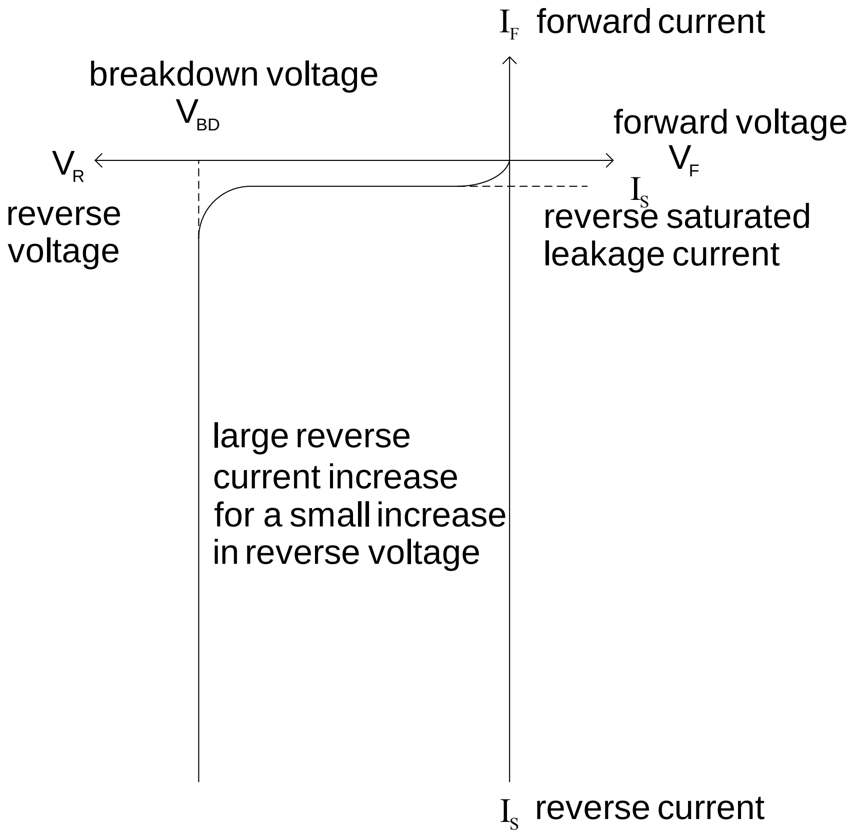
  Large V_R → Minority carriers are vibrating strongly and moving fast.

  $V_R > V_{BD}$ → The minority carriers are moving very fast and vibrating very strongly that when they collide with atoms and ions, the energy that they passed to these atoms and ions will cause their valence electrons to breakaway from them. An avalanche of electron-hole pairs (minority carriers) generated. Reverse current will be very large.

  Reverse breakdown = avalanche breakdown because of the multiplication or avalanche of current that occurs.



I-V characteristic of the reverse bias p-n junction.



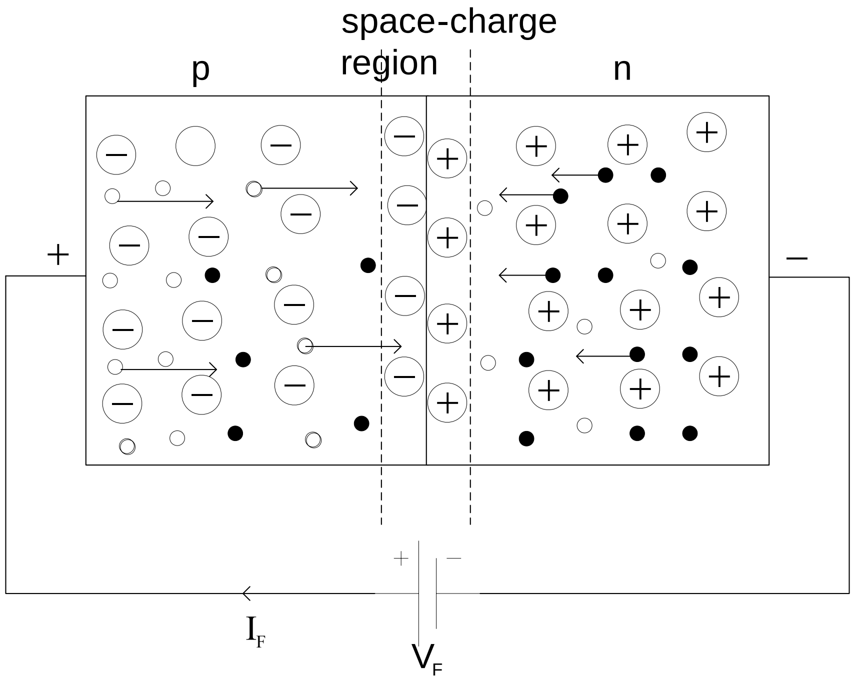
Forward biased p-n junction

Majority carriers will move toward the junction as the holes in p will be attracted to the –ve terminal and electrons in n will be attracted to the +ve terminal of the voltage supply. When the majority carriers enter the space-charge region, the holes from p will neutralize the –ve ions and the electrons from n will neutralize the +ve ions.

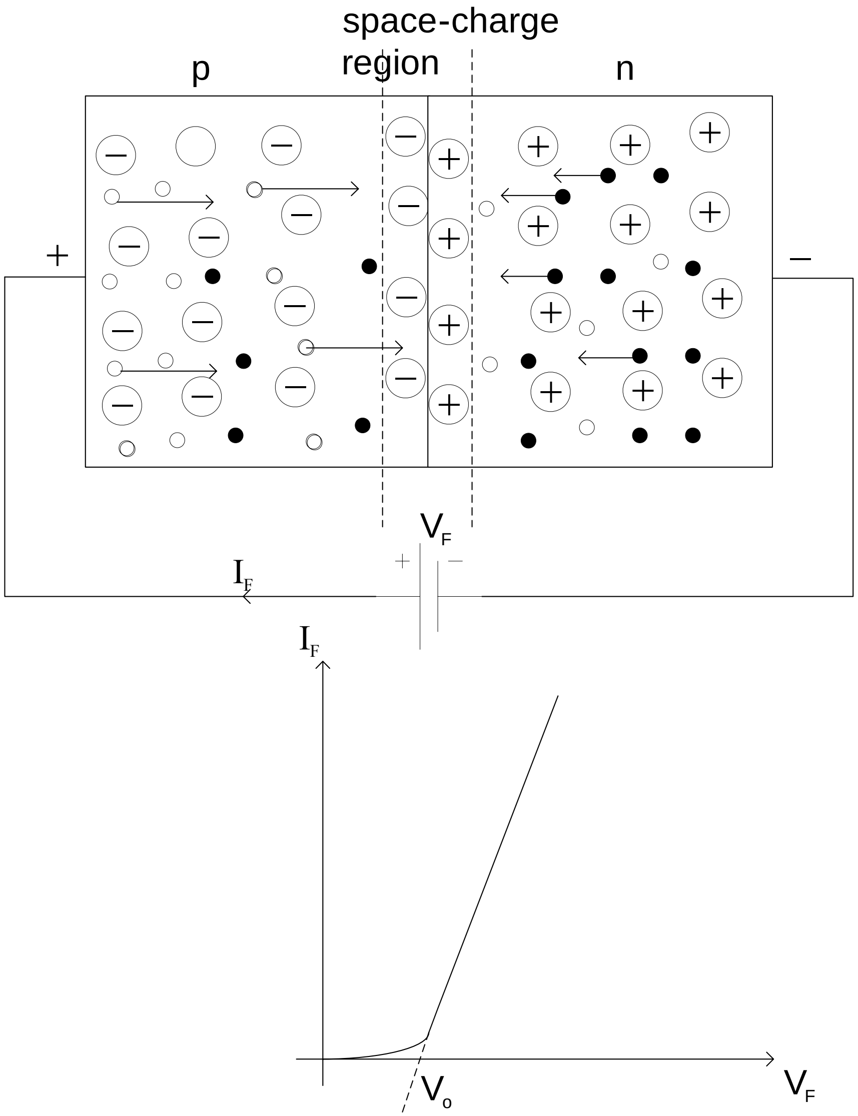
Effects:

1. Depletion region ↓
2. Potential barrier ↓
3. More majority carriers can overcome the potential barrier and cross the p-n junction.
4. Majority carrier current ↑.

$V_F \uparrow I_F \uparrow$.



- If V_F is large enough ($V_F > V_o$), the potential barrier becomes negligible. Hence, there is no longer a constraint for the majority carriers to cross the junction. A small increase in V_F will produce a large increase in the forward current I_F.
- The forward bias voltage required to enable significant current to flow is > 0.3 V for the Ge and > 0.7 V for the Si. These voltages are the potential barrier voltages for the semiconductors.



In an open-circuit p-n junction, the junction is unbiased, i.e. majority carrier diffusion current = minority carrier drift current.

As both currents are flowing in the opposite direction, nett open circuit p-n junction current is 0. Under this condition, the space charge region is said to be in equilibrium.

General equation: $\boxed{\mathbf{V_{BARRIER} = V_o - V_{BIAS}}}$

where $V_{BARRIER}$ = potential barrier voltage

V_o = potential barrier voltage when there is no bias

V_{BIAS} = biasing voltage

In equilibrium: $V_{BIAS} = 0$, $V_{BARRIER} = V_o = 0.3$ V (Ge) and 0.7 V (Si).

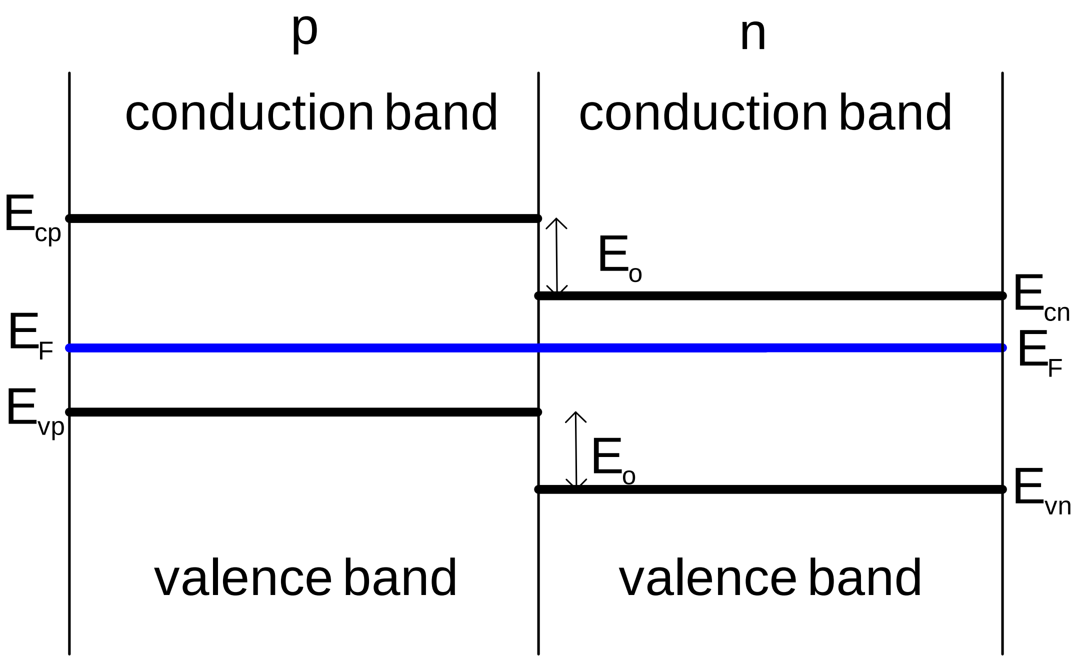
In forward bias:

For $V_{BIAS} = V_F$ and $V_F < V_o$, $V_{BARRIER}$ will decrease when V_F is increased.

In reverse bias:

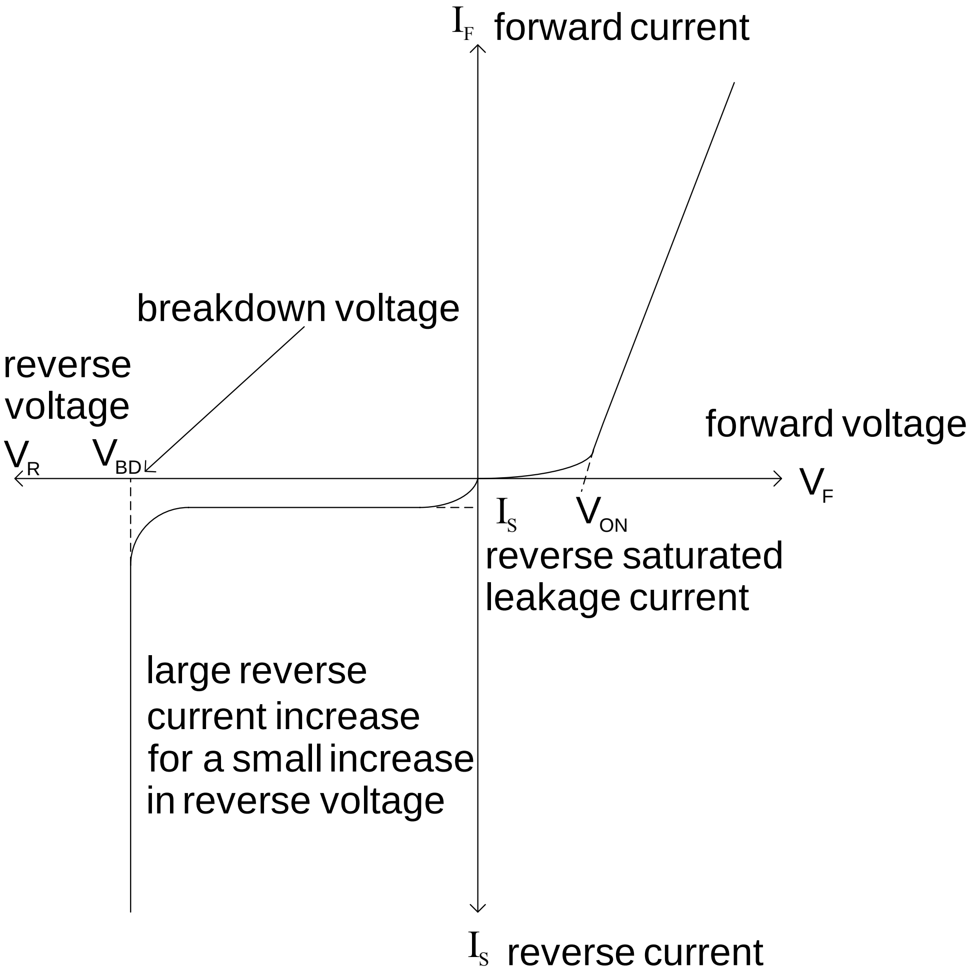
For $V_{BIAS} = V_R$, $V_{BARRIER} = V_o - (-V_R) = V_o + V_R$,$V_{BARRIER}$ will increase when V_R is increased. For $V_R \gg V_o$, $V_{BARRIER} \approx V_R$.

- $E_o = eV_o$


p
n
conduction band
conduction band
E_{cp}
E_o
E_{cn}
E_F
E_F
E_{vp}
E_o
E_{vn}
valence band
valence band

- Overall p-n junction I-V characteristic:

  The p-n junction will let current flow when it is forward biased (with the condition that $V_F > V_o$, V_o is typically written as V_{ON}). The p-n junction will prevent current from flowing when it is reverse biased. The avalanche current generated when $V_R > V_{BD}$ is an undesired current as the junction will be damaged under this condition.

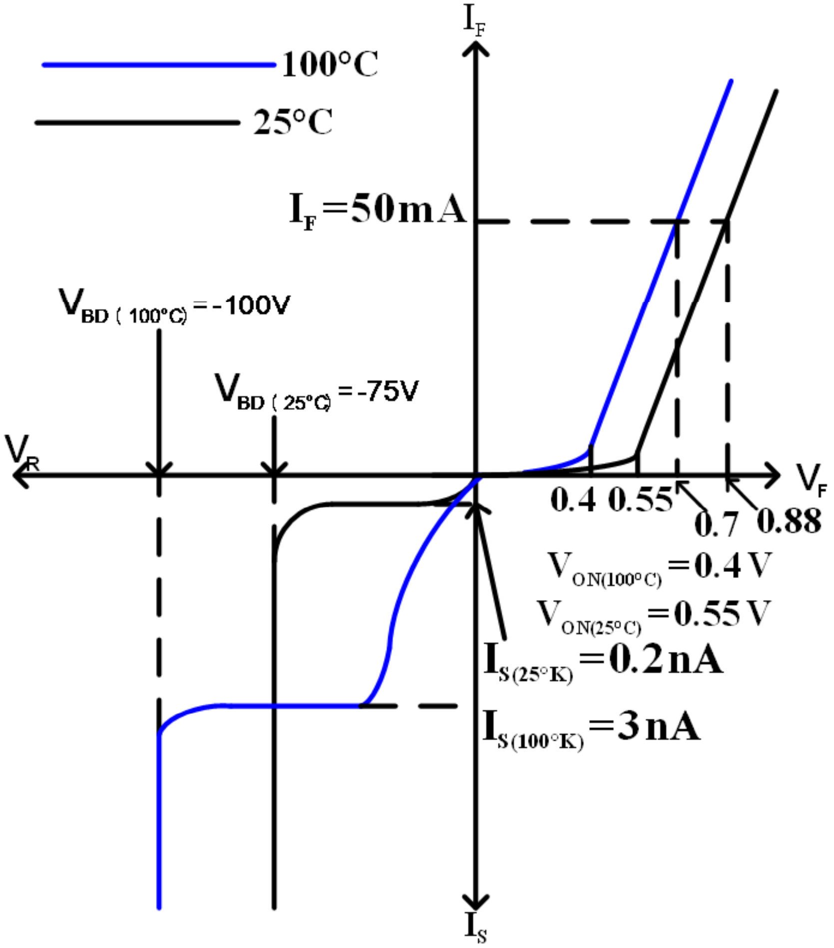


Temperature effects on the I-V characteristics of the p-n junction

I-V characteristics for the Si diode at 25°C and 100°C.

Observations:

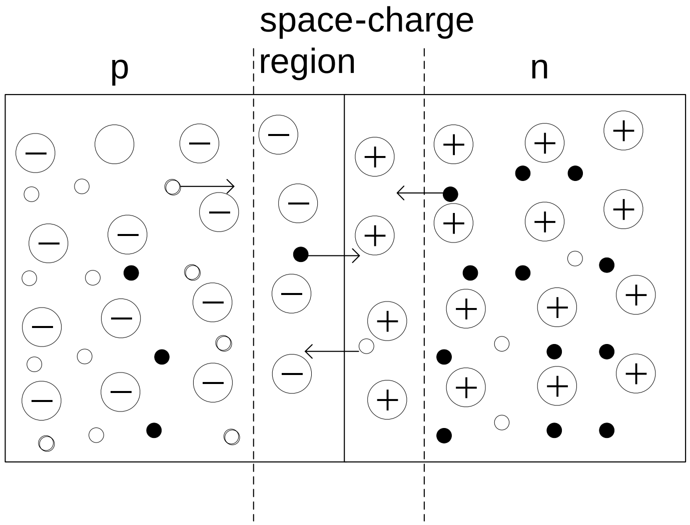
1. T ↑ V_{ON} ↓
2. T ↑ V_F ↓ to obtain the same I_F
3. T ↑ I_S ↑
4. T ↑ V_{BD} ↑

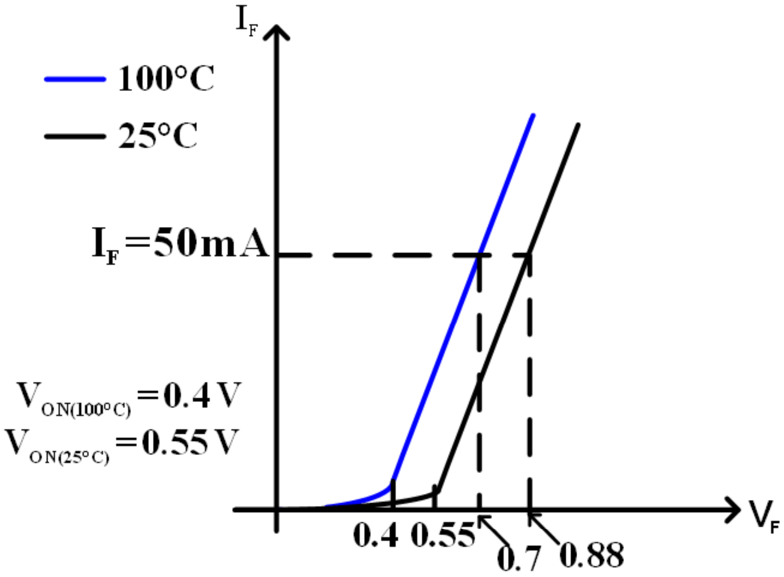


Cause for Effect 1: T ↑ V_{ON} ↓

Unbiased p-n junction has V_o = 0.3V (Ge) and 0.7V (Si).

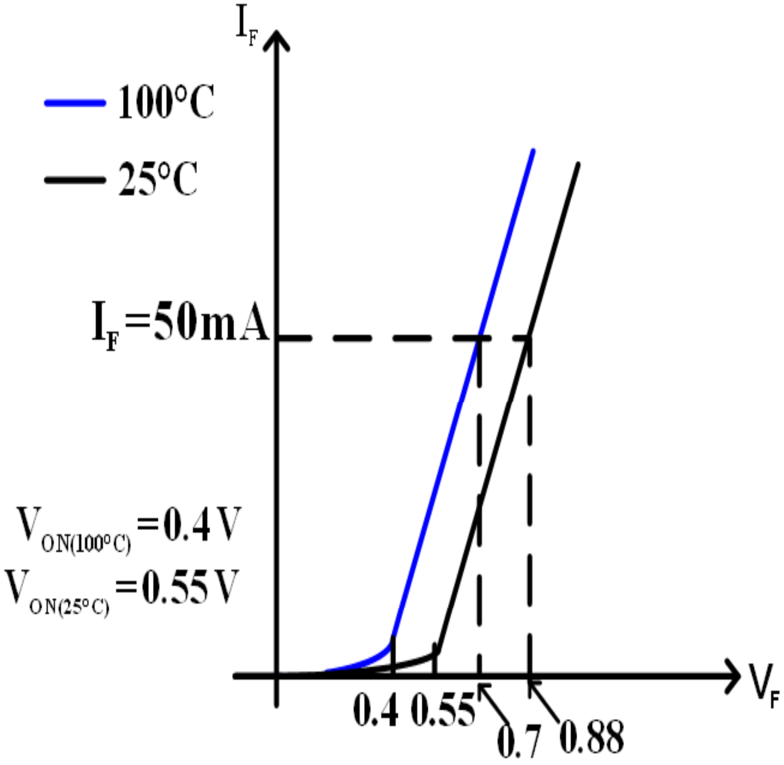
When T ↑, the no. of minority carriers (from thermal generation) ↑. The minority carriers in the space-charge region will neutralize the fixed ions in this region. Depletion region ↓, potential barrier ↓. More majority carriers can overcome this barrier. A lower V_F is required to enable significant amount of current to flow. Hence, V_{ON} ↓





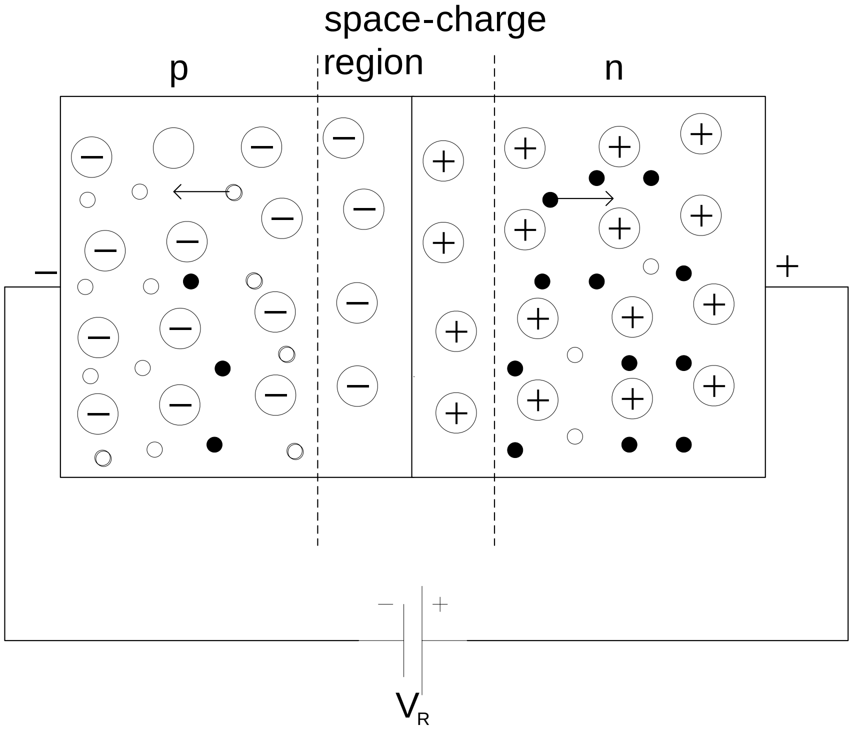
Cause for Effect 2: T↑ V_F↓ to obtain the same I_F.

The cause for this effect is very much related to the cause for Effect 1. When T ↑ V_{ON} ↓. So, a lower V_F is required to obtain the same I_F as that at a lower temperature.



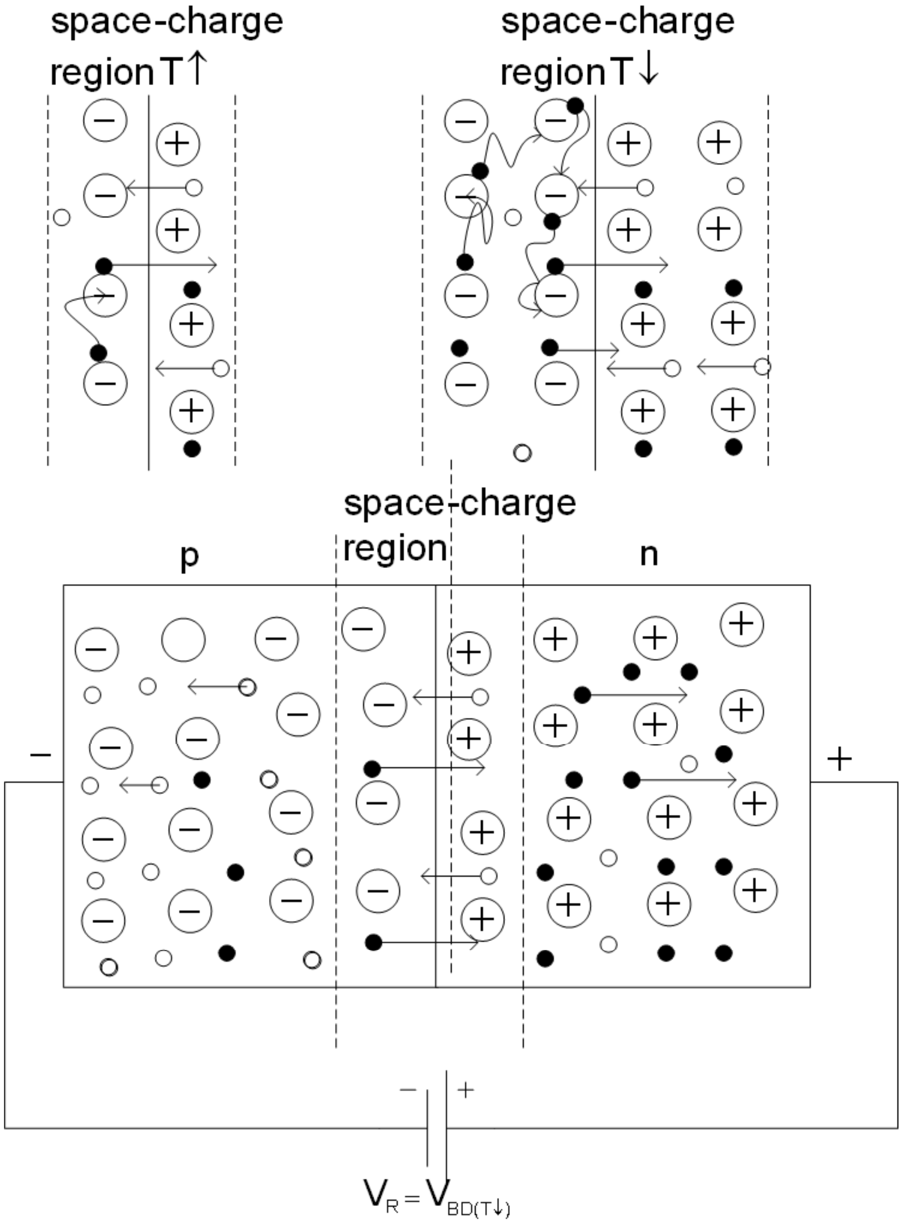
- **Cause for Effect 3: T ↑ I_S ↑.**

  The current, I_R, when the p-n junction is reverse biased is the reverse leakage current that depends on the minority carriers. At T↑, the no. of minority carriers from thermal generation ↑. The no. of minority carriers crossing the p-n junction ↑. I_R ↑. Hence, I_S ↑.



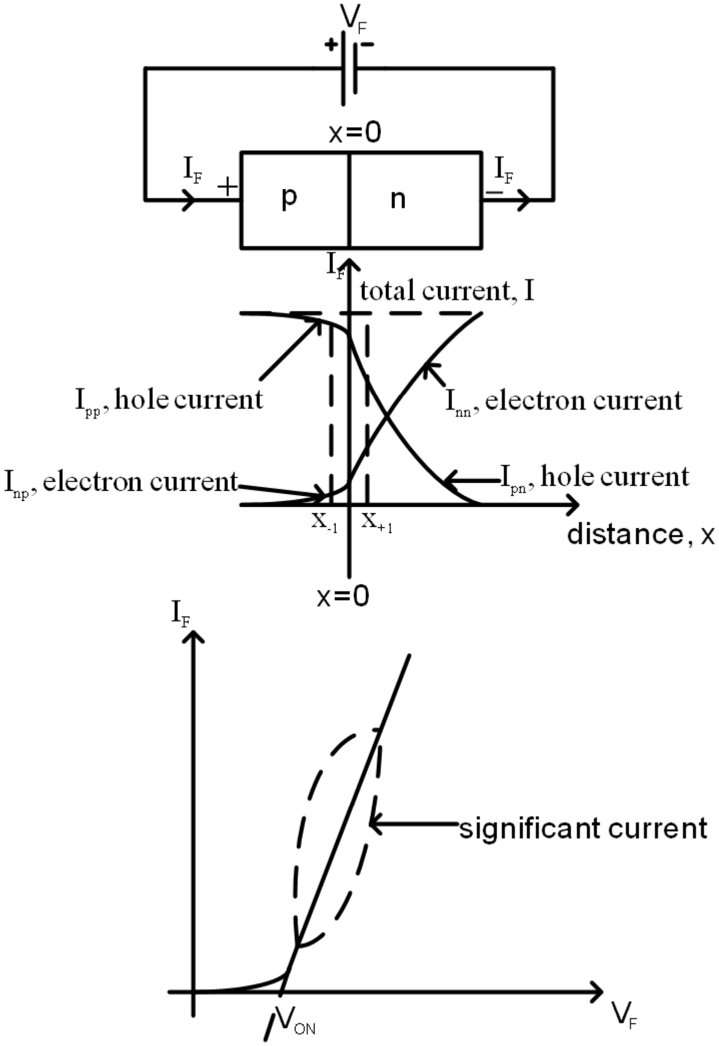
Cause for Effect 4: T ↑ V_{BD} ↑.

- Avalance breakdown occurs when the minority carriers had moved along a sufficient distance to produce the secondary and tertiary carriers by the breaking of covalent bonds.
- When T↑, the no. of minority carriers ↑. More fixed ions will be neutralized. Depletion region↓. Not enough secondary and tertiary carriers produced before the electrons cross the junction. Avalanche does not happen. Needs more voltage to enable the electrons to vibrate more and produce the secondary and tertiary carriers. Hence, V_{BD} ↑.



CURRENT COMPONENTS IN A FORWARD-BIASED P-N JUNCTION

- Diagram shows the hole and electron current components versus distance in an asymmetrical p-n junction diode ($N_A \neq N_D$).
- Current flowing through the p-n junction is the total of the hole and electron currents.
- I_{pp} = hole current in the p (majority carrier current)
- I_{np} = electron current in the p (minority carrier current)
- I_{nn} = electron current in the n (majority carrier current)
- I_{pn} = hole current in the n (minority carrier current)



In this example, $N_A > N_{D.}$

Current equations:

- At x_{-1},

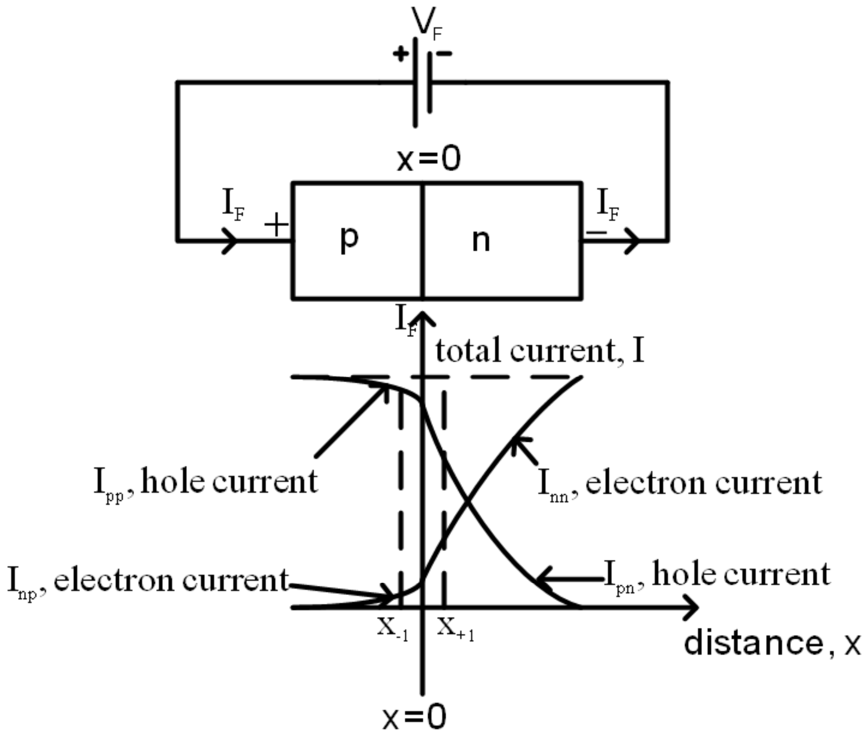
  $I_{pp}(x_{-1}) + I_{np}(x_{-1}) = I$
- At x_{+1},

  $I_{nn}(x_{+1}) + I_{pn}(x_{+1}) = I$
- In general,

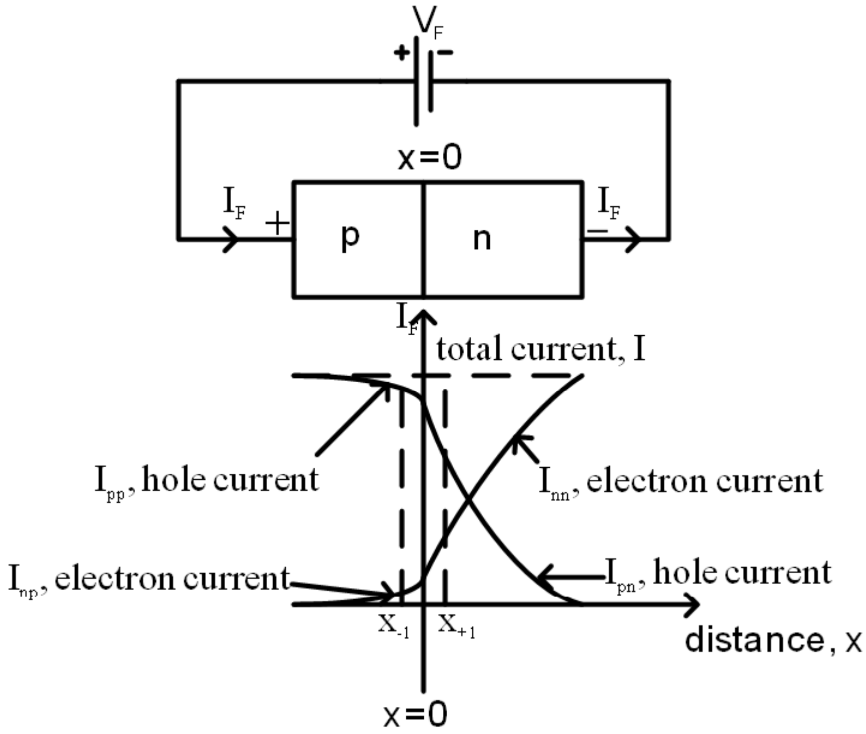
  $I_{pp}(x) + I_{np}(x) = I$

  $I_{nn}(x) + I_{pn}(x) = I$
- At $x = 0$,

  $I_{np}(0) + I_{pn}(0) = I$



- Current enters the p as a hole current but leaves the n as an electron current with the same magnitude.
- Total current is constant along the pn device but the portions contributed by the holes and electrons differ with distance.
- Current in the p-n diode is bipolar as this current is contributed by both +ve and –ve electrical carriers.



FORWARD CURRENT

- Hole current crosses the junction and enters the n as:

$$I_{pn} = \frac{AqD_p p_n}{L_p}\left(e^{\left(V/V_T\right)} - 1\right)$$

- Electron current crosses the junction and enters the p as:

$$I_{np} = \frac{AqD_n n_p}{L_n}\left(e^{\left(V/V_T\right)} - 1\right)$$

where A = cross section area

L_p , L_n = hole, electron diffusion length in n, p

p_n , n_p = hole, electron density in n, p (minority carriers)

q = electronic charge, 1.6×10^{-19} C

D_p , D_n =hole, electron diffusion coefficient

V = forward biasing voltage,

V_T = temperature equivalent voltage

= $kT/q \approx 26$ mV at T = 300°K,

k = Boltzmann constant = 1.38×10^{-23} J/°K