LECTURE 12

-p-n Junction

Topics to be covered

- P-n Junction

P-n Junction

- The p-n junction is the basic element of all bipolar devices. Its main electrical property is that it rectifies (allow current to flow easily in one direction only).The p-n junction is often just called a DIODE. Applications;

  - >photodiode, light sensitive diode,
  - >LED- ligth emitting diode,
  - >varactor diode-variable capacitance diode

The formation of p-n junction :

- The p-n junction can be formed by pushing a piece of p-type silicon into close contact with a piecce of n-type silicon. But forming a p-n junction is not so simply. Because;

1) There will only be very few points of contact and any current flow would be restricted to these few points instead of the whole surface area of the junction.
2) Silicon that has been exposed to the air always has a thin oxide coating on its surface called the “native oxide”. This oxide is a very good insulator and will prevent current flow.
3) Bonding arrangement is interrupted at the surface; dangling bonds.

Surface states

To overcome these surface states problems

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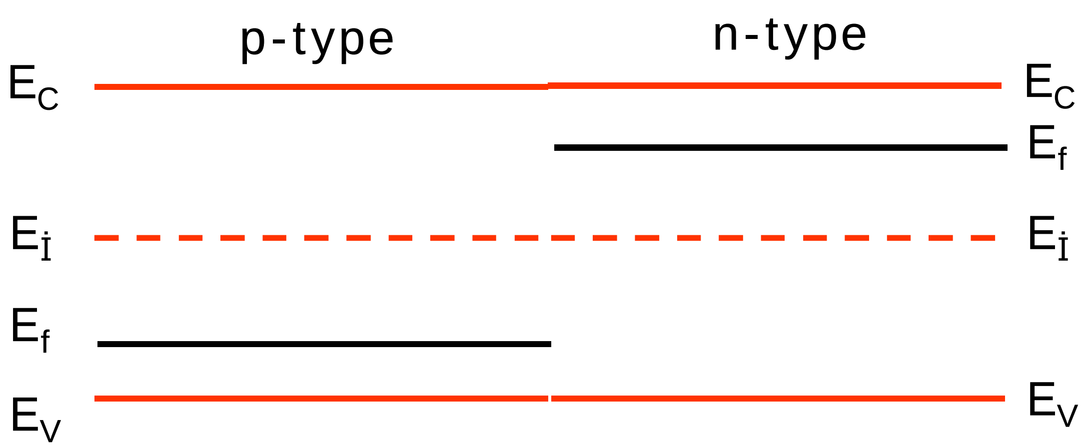
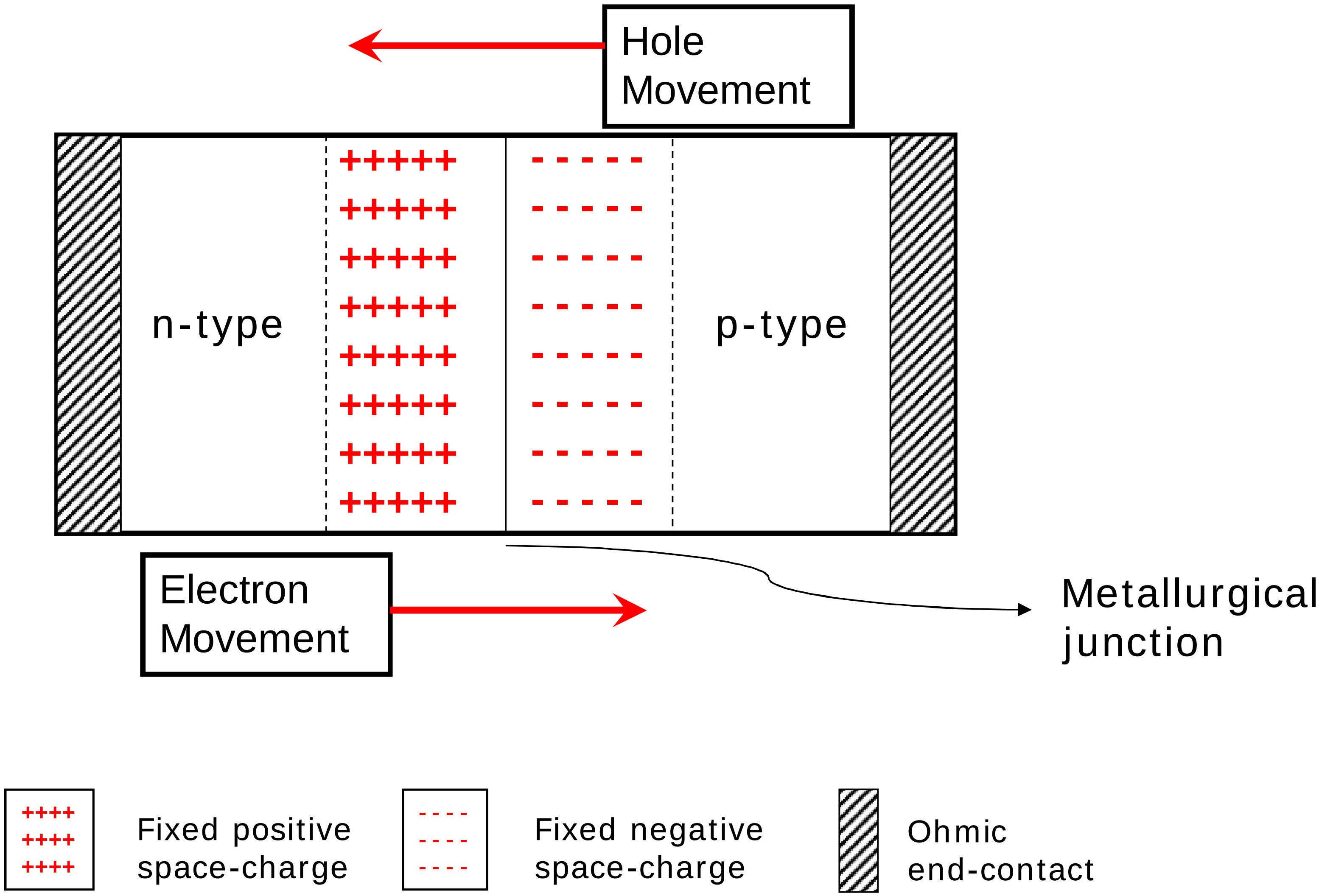
p-n junction can be formed in the bulk of the semiconductor, away from the surface as much as possible.

p – n junction



There is a big discontinuity in the fermi level accross the p-n junction.

Idealized p-n junction; recombination of the carrier and carrier diffusion



p – n junction

- Lots of electrons on the left hand side of the junction want to diffuse to the right and lots of holes on the right hand side of the junction want to move to the left.

- The donors and acceptors fixed,don’t move (unless you heat up semiconductors, so they can diffuse) because they are elements (such as arsenic and boron) which are incorporated to lattice.

- However, the electrons and holes that come from them are free to move.

Idealized p-n junction

- Holes diffuse to the left of the metalurgical junction and combine with the electrons on that side. They leave behind negatively charged acceptor centres.

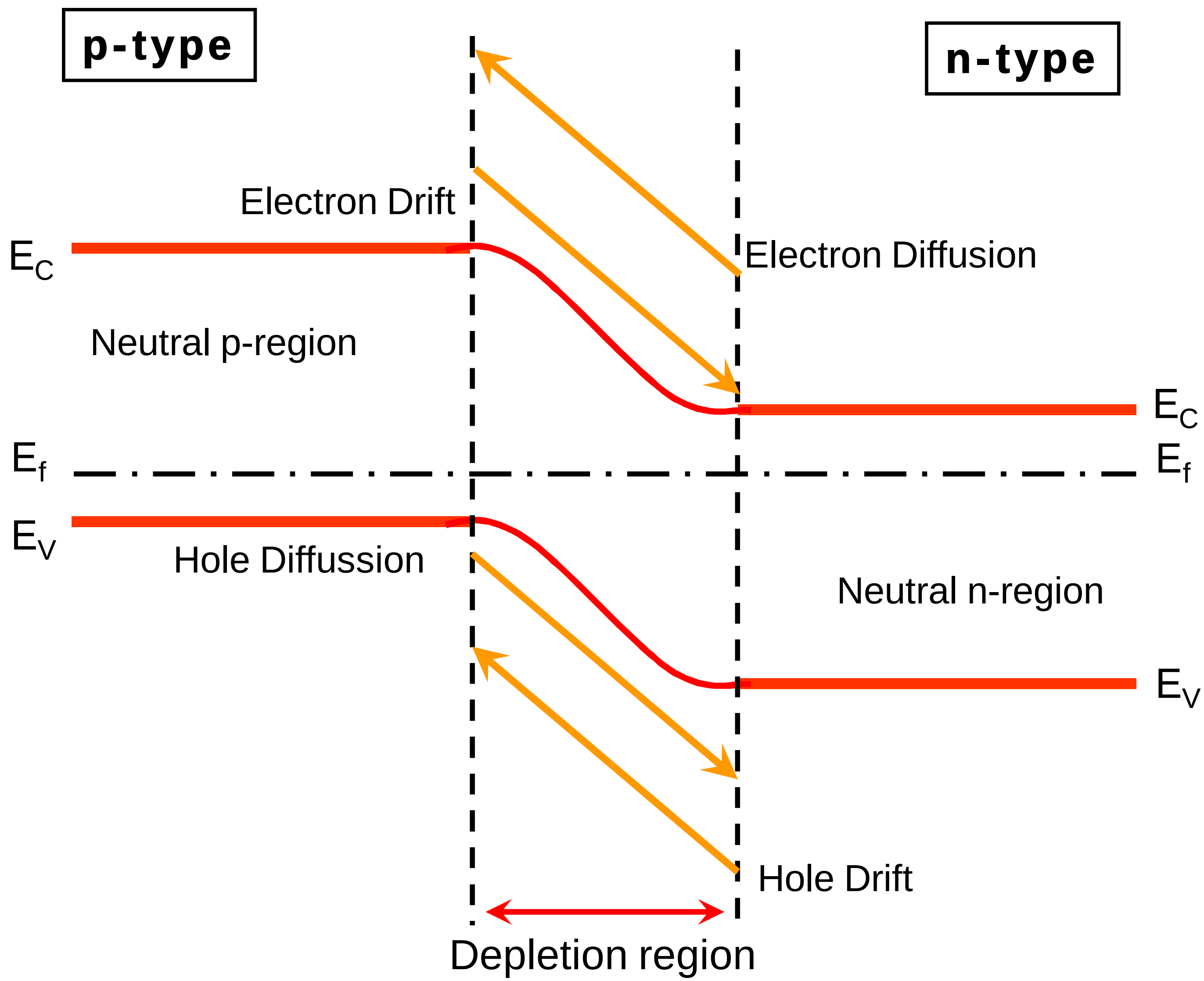
- Similarly, electrons diffusing to the right will leave behind positively charged donor centres. This diffusion process can not go on forever. Because, the increasing amount of fixed charge wants to electrostatically attract the carriers that are trying to diffuse away(donor centres want to keep the electrons and acceptor centres want to keep the holes). Equlibrium is reached.

- This fixed charges produce an electric field which slows down the diffusion process.

- This fixed charge region is known as depletion region or space charge region which is the region the free carriers have left.

- It is called as depletion region since it is depleted of free carriers.

❖Energy level diagram for the p-n junction in thermal equilibrium



Thermal equilibrium; no applied field; no net current flow

$$J_p = J_p(drift) + J_p(diffusion) = 0 \quad (1)$$

J_p *is the hole current density* $(\frac{A}{cm^2})$

Drift current is due to electric field at the junction; minority carriers.

Diffusion current is due the to concentration gradient; majority carriers.

$$J_p = q\mu_p p E_x - qD_p \frac{dp}{dx} = 0 \quad (2)$$

where

$$E_x = \frac{1}{q}\frac{dE_i}{dx} \qquad D_p = \frac{\mu_p kT}{q} \quad (Einstein\ relation)$$

Proof

$$J_p = \mu_p \left(p \frac{dE_i}{dx} - kT \frac{dp}{dx} \right) = 0 \qquad (3)$$

$$p = n_i \exp\left(\frac{E_i - E_f}{kT}\right) \Rightarrow \frac{dp}{dx} = \frac{p}{kT}\left(\frac{dE_i}{dx} - \frac{dE_f}{dx}\right)$$

$$J_p = \mu_p p \frac{dE_f}{dx} = 0 \qquad (4)$$

we conclude that $\frac{dE_f}{dx} = 0$ *which states that the Fermi Level is a CONSTANT at equilibrium.*

$$J_n = \mu_n n \frac{dE_f}{dx} = 0 \qquad (5)$$

- The drift and diffusion currents are flowing all the time. But, in thermal equilibrium, the net current flow is zero since the currents oppose each other.

- Under non-equilibrium condition, one of the current flow mechanism is going to dominate over the other, resulting a net current flow.

- The electrons that want to diffuse from the n-type layer to the p-layer have potential barier.

p – n junction barrier height, V_{bi}

- The potential barrier height V_{bi} accross a p-n junction is known as the built in potential and also as the junction potential.

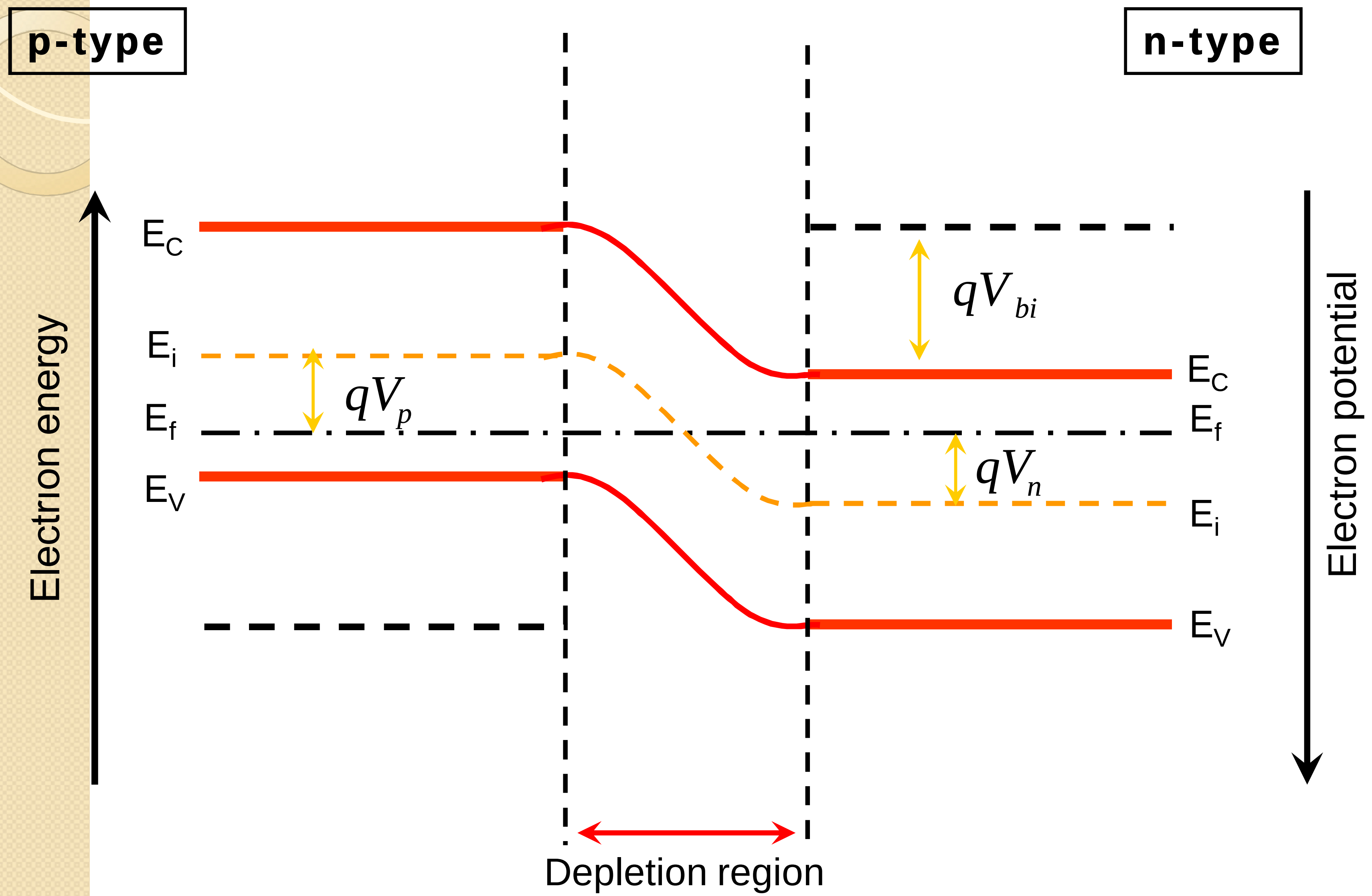
- The potential energy that this potential barrier correspond is

$$qV_{bi}$$

- Electron energy is positive upwards in the energy level diagrams, so electron potentials are going to be measured positive downwards.

- The hole energies and potentials are of course positive in the opposite directions to the electrons

p – n junction barrier height



The p – n junction barrier height

The intrinsic Fermi Level is a very useful reference level in a semiconductor.

$$qV_p = (E_i - E_f) \quad (1)$$

$$p = n_i \exp\left(\frac{E_i - E_f}{kT}\right)$$

$$\left|V_p\right| = \frac{kT}{q}\ln\frac{N_A}{n_i} \quad (2)$$

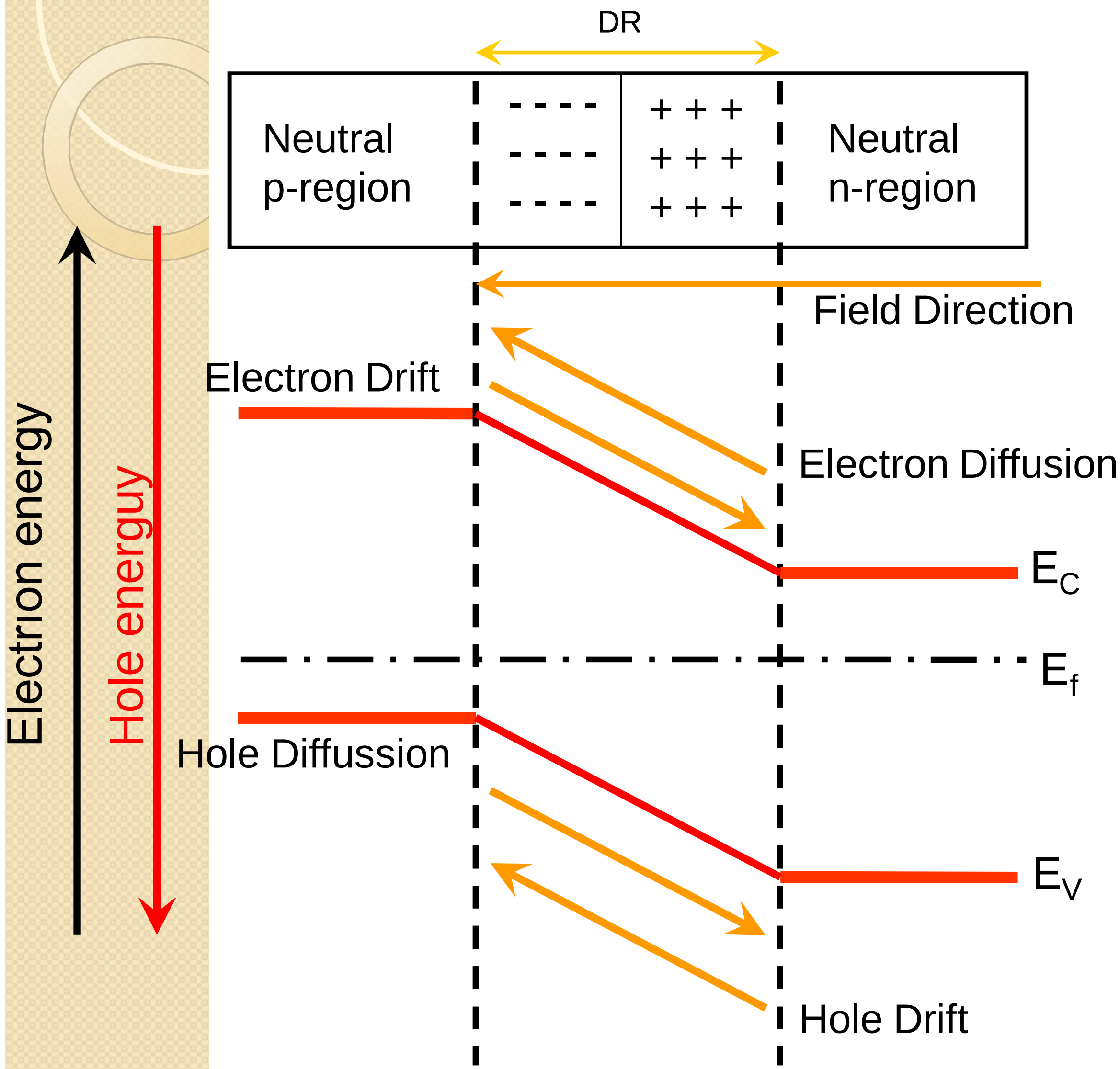
Similarly for $\left|V_n\right|$

$$\left|V_n\right| = \frac{kT}{q}\ln\frac{N_D}{n_i} \quad (3)$$

For full ionization, the built – in voltage is a sum of

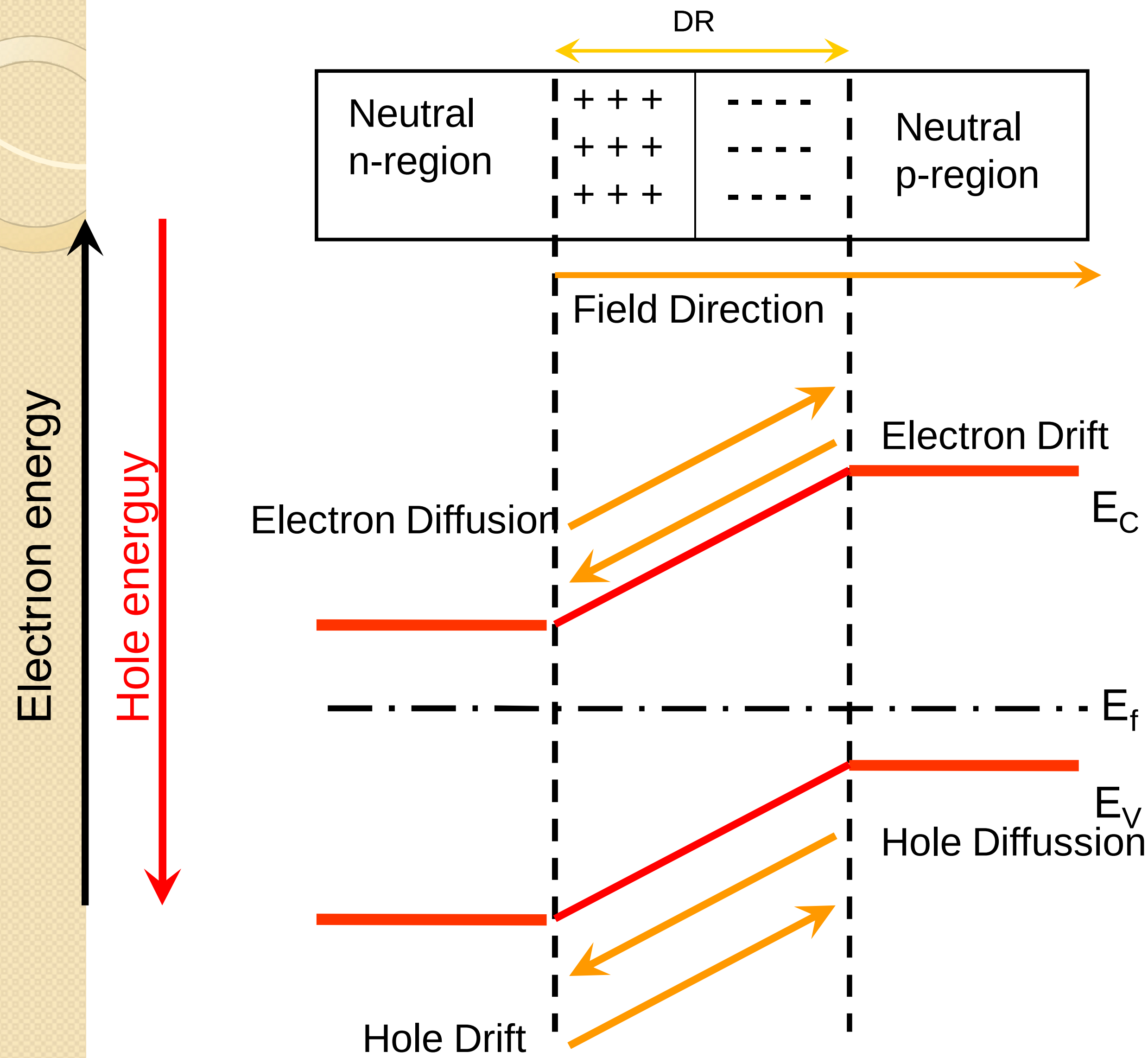
$$\left|V_{bi}\right| = \left|V_n\right| + \left|V_p\right| = \frac{kT}{q}\ln\frac{N_A N_D}{n_i^2} \quad (4)$$

p – n junction in thermal equilibrium



- Current Mechanisms,
- Diffusion of the carriers cause an electric in DR.
- Drift current is due to the presence of electric field in DR.
- Diffusion current is due to the majority carriers.
- Drift current is due to the minority carriers.

n – p junction at equilibrium



Diffusion :

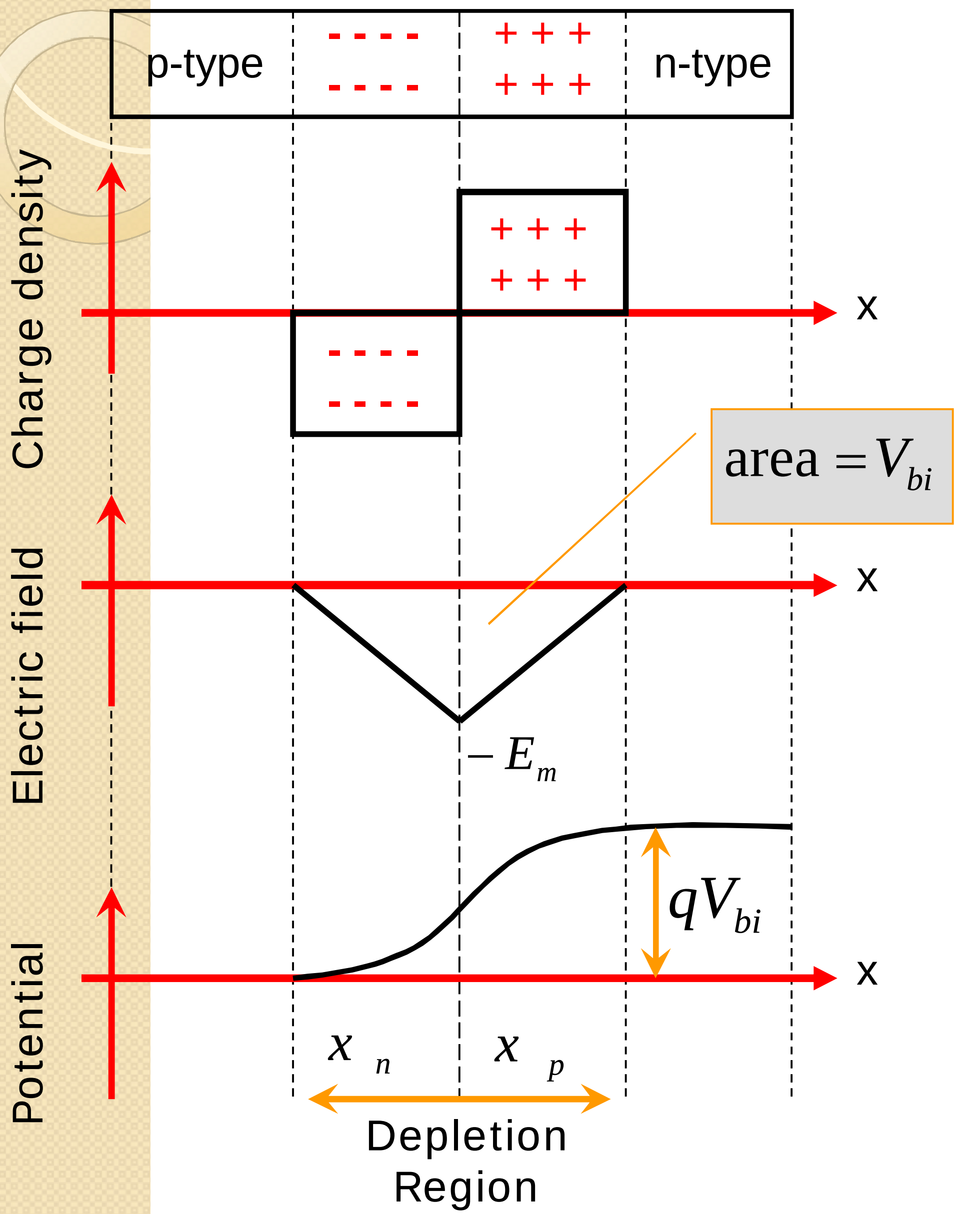
- When electrons and holes are diffusing from high concentration region to the low concentration region they both have a potential barrier. However, in drift case of minority carriers there is no potential barrier.

- Built in potential ;

$$V_{bi} = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$$

At fixed T, V_{bi} is determined by the number of N_A and N_D atoms.

Depletion Approximation, Electric Field and Potential for pn junction



- At equilibrium, there is no bias, i.e. no applied voltage.
- The field takes the same sign as the charge
- The sign of the electric field is opposite to that of the potential ;

$$E_v = -\frac{dV_n}{dx}$$

Depletion Approximation, Electric Field and Potential for pn junction

- Charge density is negative on p-side and positive on n-side.

- As seen from the previous diagram, the charge distribution is very nice and abrupt changes occur at the depletion region (DR) edges. Such a junction is called as an ***abrupt junction*** since the doping abruptly changes from p- to n-type at the metallurgical junction (ideal case).

$$x_n \rightarrow \text{ the width of the DR on n-side}$$

$$x_p \rightarrow \text{ the width of the DR on p-side}$$

Depletion Approximation, Electric Field and Potential for pn junction

- In reality, the charge distribution tails-off into the neutral regions, i.e. the charge distrubition is not abrupt if one goes from depletion region into the neutral region. This region is called as a transition region and since the transition region is very thin, one can ignore the tail-off region and consider the change being abrupt. So this approximation is called as DEPLETION APPROXIMATION.

Depletion Approximation, Electric Field and Potential for pn junction

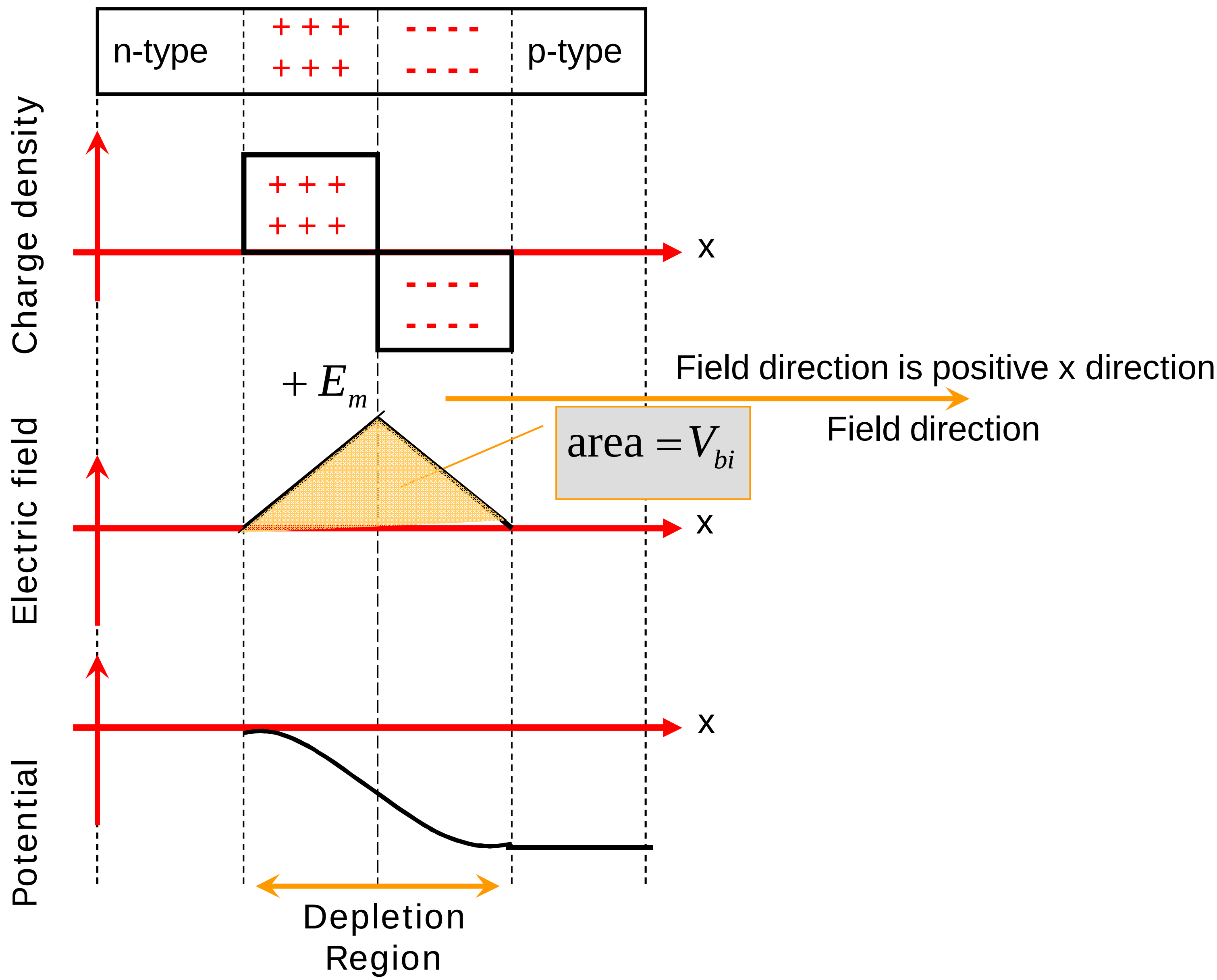
Electric Field Diagram :

- The electric field is zero at the edge of the DR and increases in negative direction. At junction charge changes its sign so do electric field and the magnitude of the field decreases (it increases positively).

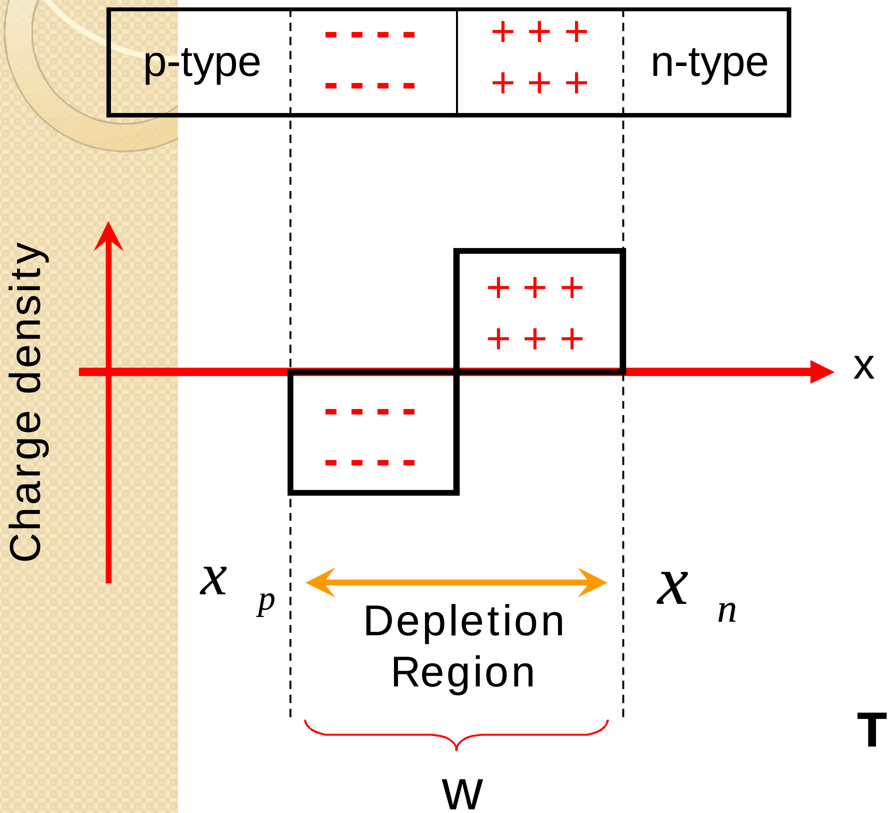
Potential Diagram :

- Since the electric field is negative through the whole depletion region ,DR, the potential will be positive through the DR. The potential increases slowly at left hand side but it increases rapidly on the right hand side. So the rate of increase of the potential is different an both sides of the metallurgical junction. This is due to the change of sign of charge at the junction.

Depletion Approximation, Electric Field and Potential for np junction



Abrupt junction



- The amount of uncovered negative charge on the left hand side of the junction must be equal to the amount of positive charge on the right hand side of the metalurgical junction. Overall space-charge neutrality condition;

$$N_A x_p = N_D x_n$$

The higher doped side of the junction has the narrower depletion width

when $N_A = N_D \Rightarrow x_n = x_p$

Abrupt junction

- x_n and x_p is the width of the depletion layer on the n-side and p-side of the junction, respectively.

When $N_D >> N_A$ (unequal impurity concentrations)

and $x_p >> x_n$, $W \cong x_p$

- Unequal impurity concentration results an unequal depletion layer widths by means of the charge neutrality condition;

$$N_A . x_p = N_D . x_n$$

W = total depletion region

Abrupt junction

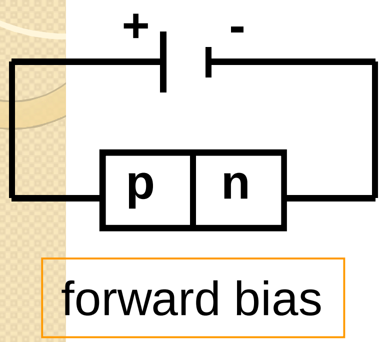
When $N_A >> N_D \Rightarrow \quad x_n >> x_p \quad \Rightarrow W \cong x_n$

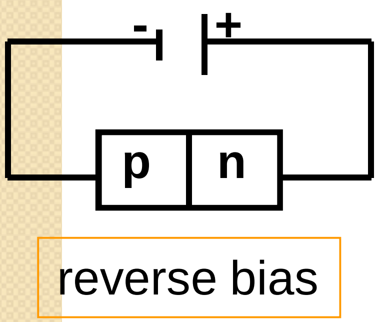
- Depletion layer widths for n-side and p-side

$$x_n = \frac{1}{N_D}\sqrt{\frac{2\varepsilon_{Si} V_{bi} N_A N_D}{q(N_A + N_D)}}$$

$$x_p = \frac{1}{N_A}\sqrt{\frac{2\varepsilon_{Si} V_{bi} N_A N_D}{q(N_A + N_D)}}$$

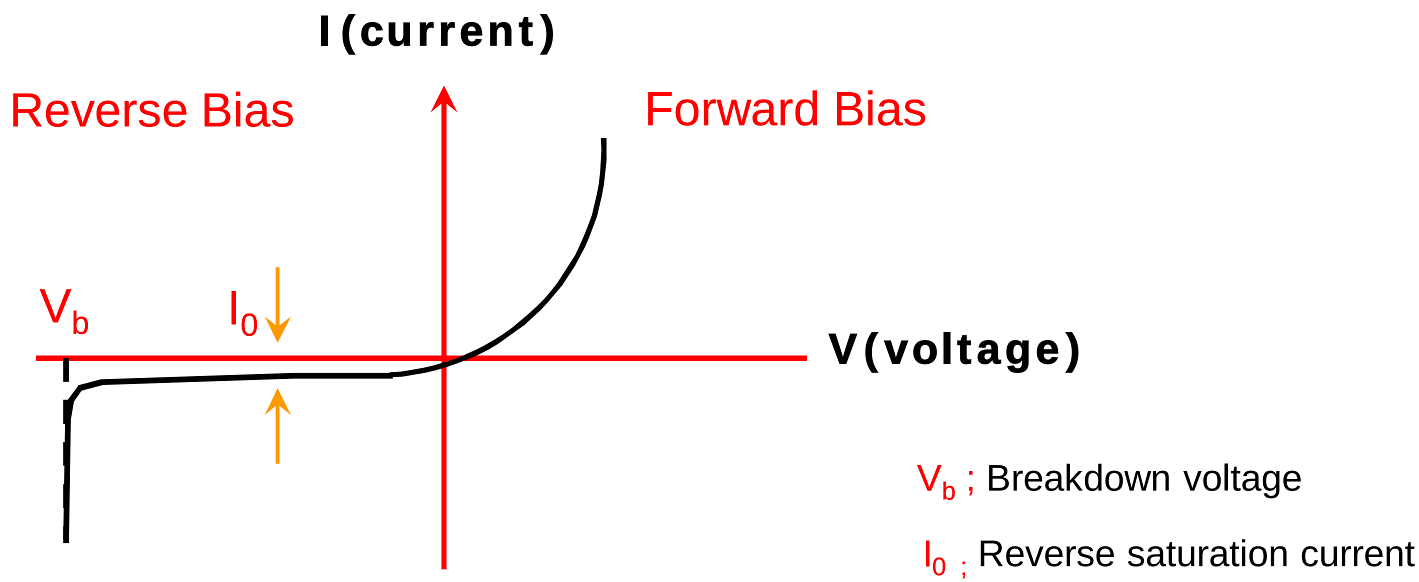
Appliying bias to p-n junction





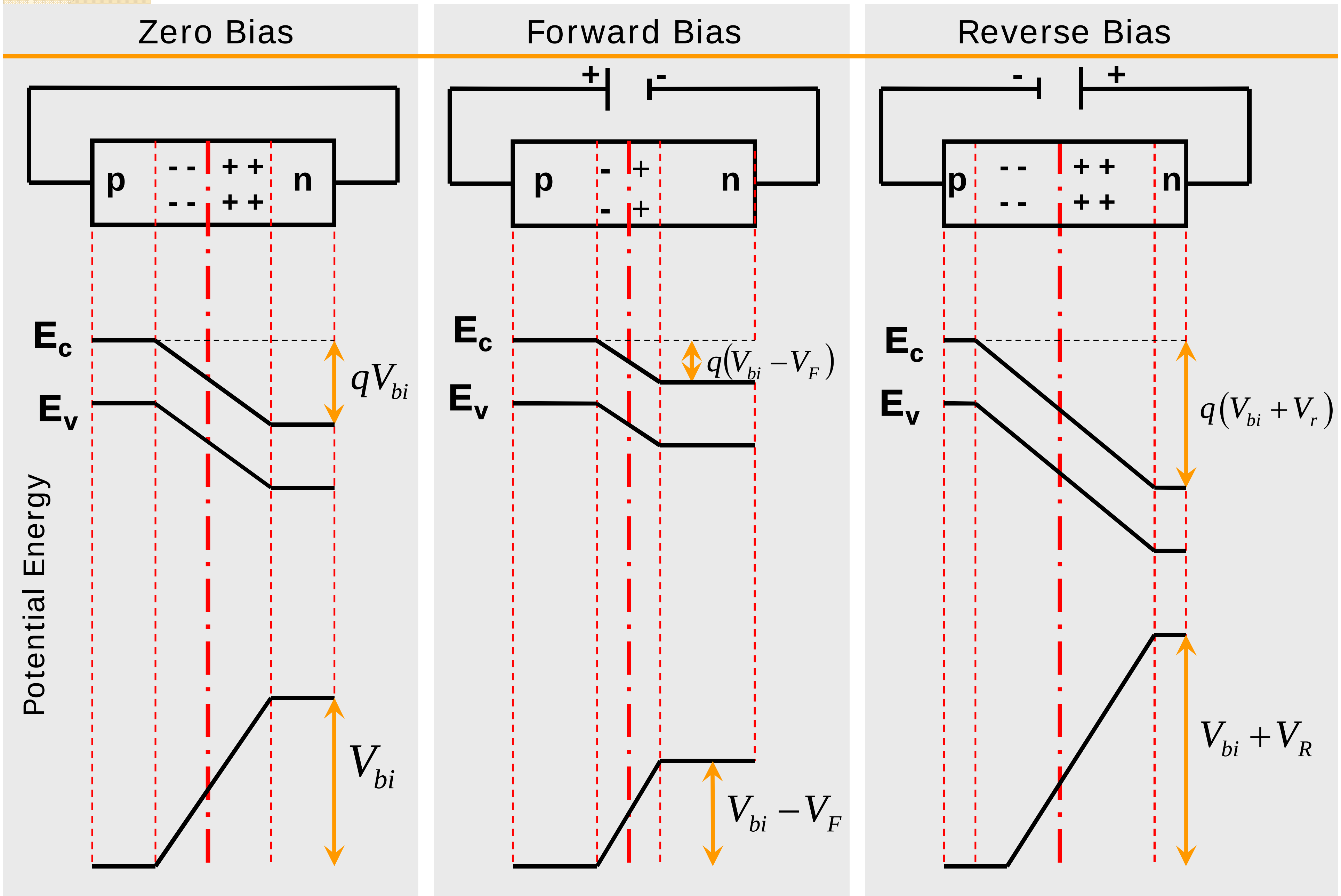
- How current flows through the p-n junction when a bias (voltage) is applied.
- The current flows all the time whenever a voltage source is connected to the diode. But the current flows rapidly in forward bias, however a very small constant current flows in reverse bias case.

Appliying bias to p-n junction



- There is no turn-on voltage because current flows in any case. However , the turn-on voltage can be defined as the forward bias required to produce a given amount of forward current.
- If 1 m A is required for the circuit to work, 0.7 volt can be called as turn-on voltage.

Appliying bias to p-n junction



Appliying bias to p-n junction

$$V_F \rightarrow \text{forward voltage}$$
$$V_R \rightarrow \text{reverse voltage}$$

- When a voltage is applied to a diode , bands move and the behaviour of the bands with applied forward and reverse fields are shown in previous diagram.

Forward Bias

- Junction potential reduced
- Enhanced hole diffusion from p-side to n-side compared with the equilibrium case.
- Enhanced electron diffusion from n-side to p-side compared with the equilibrium case.
- Drift current flow is similar to the equilibrium case.
- Overall, a large diffusion current is able to flow.
- Mnemonic. Connect positive terminal to p-side for forward bias.

- Drift current is very similar to that of the equilibrium case. This current is due to the minority carriers on each side of the junction and the movement minority carriers is due to the built in field accross the depletion region.

Reverse Bias

- Junction potential increased
- Reduced hole diffusion from p-side to n-side compared with the equilibrium case.
- Reduced electron diffusion from n-side to p-side compared with the equilibrium case
- Drift current flow is similar to the equilibrium case.
- Overall a very small reverse saturation current flows.
- Mnemonic. Connect positive terminal to n-side for reverse bias.

Ideal diode equation

- "o" subscript denotes the equilibrium carrier concentration.

$n_{no} \rightarrow$ equilibrium electron concentration in n - type material.

$n_{po} \rightarrow$ equilibrium electron concentration in p - type material.

$p_{po} \rightarrow$ equilibrium hole concentration in p - type material.

$p_{no} \rightarrow$ equilibrium hole concentration in n - type material.

$$n.p = n_i^2$$

Ideal diode equation

$$n.p = n_i^2$$

❖ At equilibrium case (no bias)

$$n_{no}.p_{no} = n_i^2 \rightarrow n - type\ material \qquad (1)$$

$$n_{po}.p_{po} = n_i^2 \rightarrow p - type\ material \qquad (2)$$

Ideal diode equation

$$V_{bi} = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$$ assuming full ionization

$$N_A \cong p_{po} \ ; N_D \cong n_{no}$$ majority carriers

$$V_{bi} = \frac{kT}{q} \ln \frac{p_{po} . n_{no}}{n_i^2}$$

$$n_{no} . p_{no} = n_i^2$$ for n-type

$$V_{bi} = \frac{kT}{q} \ln \frac{p_{po}}{p_{no}} \Rightarrow p_{po} = p_{no} \exp\left(\frac{qV_{bi}}{kT}\right) \quad (3)$$

Ideal diode equation

$$\textit{Similarly, from equation } (2)$$

$$V_{bi} = \frac{kT}{q} \ln \frac{p_{po} . n_{no}}{n_i^2} \qquad n_{po} . p_{po} = n_i^2$$

$$V_{bi} = \frac{kT}{q} \ln \frac{n_{no}}{n_{po}} \Rightarrow n_{no} = n_{po} \exp\left(\frac{qV_{bi}}{kT}\right) \quad (4)$$

This equation gives us the equilibrium majority carrier concentration.

Ideal diode equation

What happens when a voltage appears across the p-n junction ?

- Equations (3) and (4) still valid but you should drop (0) subscript and change V_{bi} with

i. $V_{bi} - V_F$ if a forward bias is applied.
ii. $V_{bi} + V_R$ if a reverse bias is applied.

V_F : forward voltage

V_R : reverse voltage

With these biases, the carrier densities change from equilibrium carrier densities to non- equilibrium carrier densities.

Ideal diode equation

- Non-equilibrium majority carrier concentration in forward bias;

$$p_p = p_n \exp\left(\frac{q(V_{bi} - V_F)}{kT}\right)$$

For example; n_n for reverse bias

$$n_n = n_p \exp\left(\frac{q(V_{bi} + V_R)}{kT}\right)$$

- When a voltage is applied; the equilibrium n_{no} changes to the non equilibrium n_n.

Junction breakdown or reverse breakdown

- An applied reverse bias (voltage) will result in a small current to flow through the device.
- At a particular high voltage value, which is called as breakdown voltage V_B, large currents start to flow. If there is no current limiting resistor which is connected in series to the diode, the diode will be destroyed. There are two physical effects which cause this breakdown.

1) Zener breakdown is observed in highly doped p-n junctions and occurs for voltages of about 5 V or less.

2) Avalanche breakdown is observed in less highly doped p-n junctions.

Zener breakdown

- Zener breakdown occurs at highly doped p-n junctions with a tunneling mechanism.

- In a highly doped p-n junction the conduction and valance bands on opposite side of the junction become so close during the reverse-bias that the electrons on the p-side can tunnel from directly VB into the CB on the n-side.

- Avalanche breakdown mechanism occurs when electrons and holes moving through the DR and acquire sufficient energy from the electric field to break a bond i.e. create electron-hole pairs by colliding with atomic electrons within the depletion region.
- The newly created electrons and holes move in opposite directions due to the electric field and thereby add to the existing reverse bias current. This is the most important breakdown mechanism in p-n junction.