Engineering Physics (2025)
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Module 2 Unit 2: Optoelectronics

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M2U2 Plan

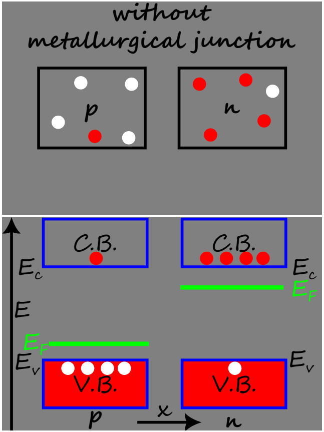
1. p-n junction diode – forward and reverse conditions

M2U2 Plan

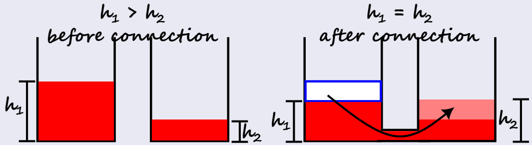
1. p-n junction diode – forward and reverse conditions

Isolated p-type and n-type semiconductors

- The Fermi level of p-type semiconductor is closer to the valence band edge E_v.
- The Fermi level of n-type semiconductor is closer to the conduction band edge E_c.



Analogy of gravitational force

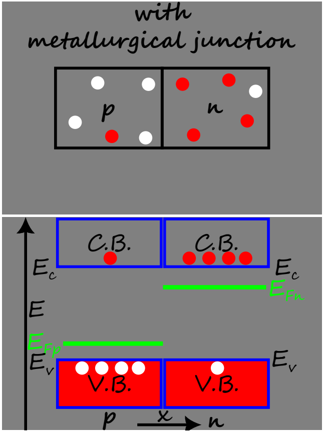


- When the glasses are connected, the the gravitational force acts as driving force to reach equilibrium.
- In the case of semiconductors, the driving force to reach equilibrium is E_F.

pn junction – Metallurgical junction

Definition

Metallurgical junction is defined as the interface between the p-type and n-type semiconductors.



- Upon the formation of metallurgical junction, there is a difference in the Fermi level in both the regions.
- The n region has higher Fermi level E_{Fn} than p region E_{Fp}, because there are more electrons in the n-region.

pn junction at zero bias

pn junction – at zero bias

Definition

Zero bias condition is considered when external battery is not connected across p-region and n-region.

- The word voltage bias is used in the context of electricity to refer to external force.
- At zero voltage bias, there is **no application of external force** on the charge carriers.
- However, there are two internal forces at play –
  1. Diffusion forces due to gradients in concentration of charge carriers.
  2. Drift forces due to internal electric fields.
- The interplay of these internal forces leads to net zero force on charge carriers at thermal equilibrium.

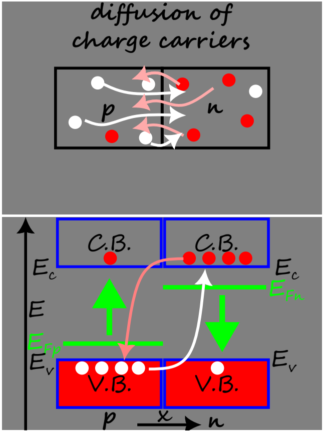
Key Insight

At zero bias, there is interplay of internal drift and diffusion forces.

pn junction – Diffusion

Definition

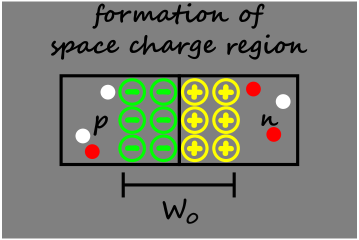
Diffusion is the net movement of particles from a region of higher concentration to a region of lower concentration.



- The difference in Fermi level acts as a "driving force" so that electrons from n-region **diffuse** into the p-region.
- By similar analysis, holes from p-region diffuse into the n-region.
- Diffusion of electrons from n-region lowers its Fermi level E_{Fn}.
- Diffusion of holes from p-region raises its Fermi level E_{Fp}.

Definition

- **Space charge region**, also called the **depletion region**, is the region created as a result of diffusion of free charge carriers across the metallurgical junction.
- The width of the depletion region is called depletion region width W_0.



- Due to the diffusion of mobile charge carriers, their **ionic counterparts** are left without partners.
- Space charge region is also called the **depletion region** since the region is depleted [a] of the free charge carriers.

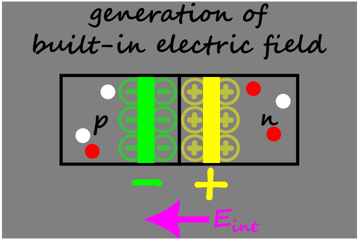
[a] deplete means decrease or remove.

- The depletion region consists of positively charged donor ions on the n-side of the junction and negatively charged acceptor ions on the p-side of the junction.

pn junction at zero bias – Built-in electric field

Definition

Built-in electrical field, also called internal electric field E_{int} is the electric field generated due to the oppositely charged regions on either side of the metallurgical junction.

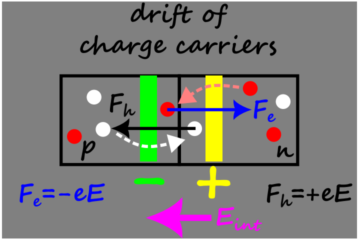


- Within the depletion region, the oppositely charged ions on either side of junction can be considered as plates of a capacitor.
- Since the plates are charged, a **built-in electric field** is generated.
- The built-in electric field is directed from n-region to p-region.
- E_{int} prevents further build up of space charge due to diffusion as it opposes the diffusion of electrons from n-region into p-region and vice versa.

pn junction at zero bias – Drift

Definition

Drift is the net movement of charged particles due to the application of electric field.

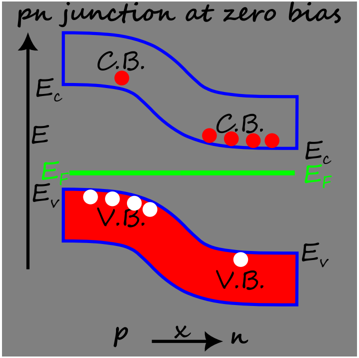


- Consider a diffused electron that is present in the p side of the depletion region.
- Since the built-in electric field is directed from n-region to p-region, the electric force is directed from p-region to n-region.
- Electron drift backs to the n-region.
- The diffusion force is counterbalanced by the drift force.
- Similar analysis applies to the diffused hole.

Problem

Prove the counterbalancing effect of drift and diffusion for holes.

pn junction at zero bias – Thermal equilibrium



Definition

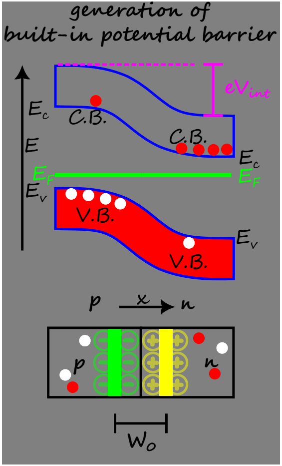
Thermal equilibrium occurs when the net force on the system is zero.

- Since the difference in Fermi level is a "driving" force, when the system reaches thermal equilibrium, the net force is zero.
- This implies the Fermi level is a constant throughout the system at thermal equilibrium.
- Since the external force is zero at zero bias, the pn junction is at thermal equilibrium.

Key Insight

At thermal equilibrium, E_F is a constant.

pn junction at zero bias – Built-in potential barrier



Definition

Built-in potential barrier V_{int} is the potential difference generated across the oppositely charged halves of the depletion region.

- If we model the depletion region as a capacitor with electric field E_{int} between the plates and the separation between the plates is W, then the potential difference across the plates is given by

$$E_{\text{int}} = \frac{V_{\text{int}}}{W_0} \Rightarrow V_{\text{int}} = E_{\text{int}} W_0$$

Key Insight

Potential barrier is proportional to the built-in electric field.

pn junction at non-zero bias

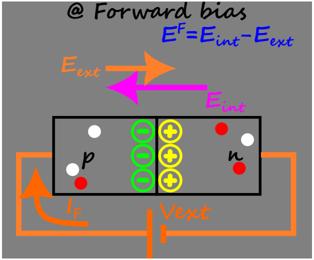
pn junction – at non-zero bias

- At non-zero voltage bias, there is **an application of external force** on the charge carriers. As a result, the pn junction cannot attain thermal equilibrium.
- Since there is no thermal equilibrium, the Fermi energy is not a constant across the pn junction.
- Since the direction of built-in electric field is from n-region to p-region, the behaviour of p-n junction is different when the external field E_{ext} is parallel or anti-parallel to the built-in electric field E_{int}.
  1. $E_{\text{ext}} \uparrow\downarrow E_{\text{int}}$ corresponds to forward biasing.
  2. $E_{\text{ext}} \uparrow\uparrow E_{\text{int}}$ corresponds to reverse biasing.

Key Insight

At non zero bias, the Fermi energy is not a constant across the pn junction.

pn junction – at forward bias

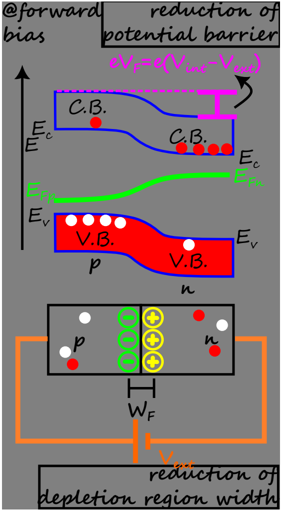


Forward
$V_F > 0$ $E^F < E_{\text{int}}$ $W_F < W_0$ $V_{\text{F}} < V_{\text{int}}$ $E_{\text{Fn}} - E_{\text{Fp}} > 0$ $I_F > 0$

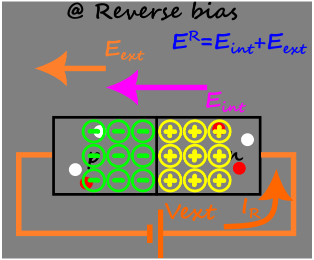
Definition

Forward bias condition is considered when the positive electrode of battery with potential V_F is connected to p-region and negative electrode is connected to n-region.

- The external bias $V_{\text{ext}} = V_F$ is from p-region to n-region.
- The external field E_{ext} is from p-region to n-region. The internal field E_{int} is **anti-parallel** to E_{ext}. The net electric field E^F is lower than the case of zero bias.
- So less space charge is created in depletion region. So we have smaller space charge width W_F.



- Since potential is proportional to electric field, potential barrier V_F is lowered.
- From the band diagram, Fermi energy of n-region E_{Fn} is higher than Fermi energy of p-region E_{Fp}.
- So electrons will move from n region to p-region. This leads to current from p-region to n-region. This is called forward bias current I_F.
- Since electrons are present in n-region this leads to **good conduction** of pn-junction.



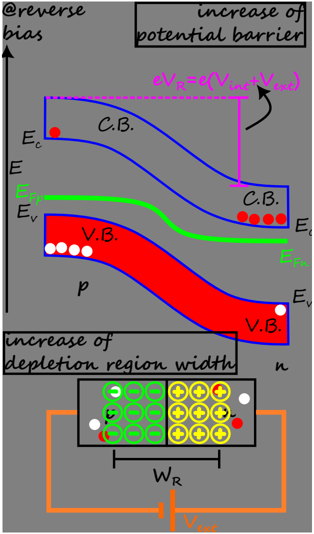
Reverse
$V_R < 0$
$E^{\mathrm{R}} > E_{\mathrm{int}}$
$V_{\mathrm{R}} > V_{\mathrm{int}}$
$E_{\mathrm{Fn}} - E_{\mathrm{Fp}} < 0$
$W_R > W_0$
$I_R < 0$

Definition

Reverse bias condition is considered when the positive electrode of battery is connected to n-region and negative electrode is connected to p-region.

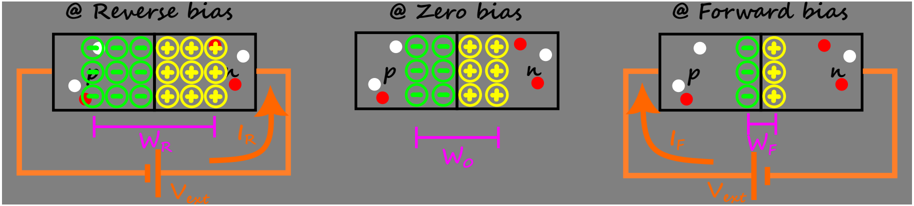
- The external bias $V_{\mathrm{ext}} = V_R$ is from n-region to p-region.
- The external field is from n-region to p-region. Under reverse bias condition, the internal field is **parallel** to the external field. The net electric field E^R is higher than the case of zero bias.
- So more space charge is created in depletion region. So we have larger space charge width W_R.

pn junction – at reverse bias



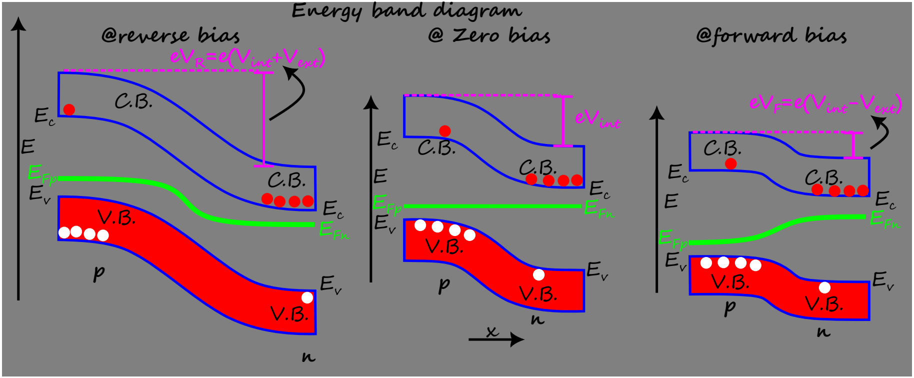
- Since potential is proportional to electric field, potential barrier V_R is raised.
- From the band diagram, Fermi energy of n-region E_{Fn} is lower than Fermi energy of p-region E_{Fp}.
- So electrons want to move from p region to n-region. But only minority carriers are there in p region.
- Since very few electrons are present in n-region this leads to **poor conduction** of pn-junction and the current is called reverse bias current I_R.

Comparison of depletion region widths at different biases



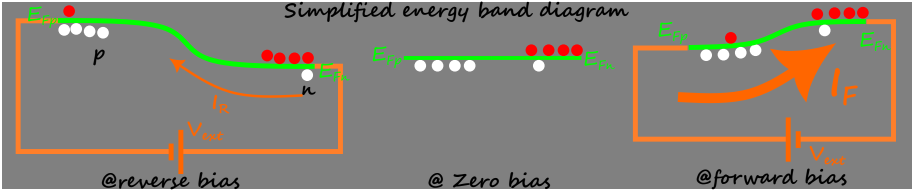
$$W_R > W_0 > W_F$$

Comparison of potential barrier at different biases



$$V_R > V_{\text{int}} > V_F$$

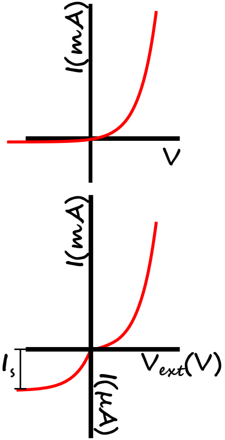
Concept of simplified energy band diagram



- Energy band diagram has many features. It is sometimes useful to represent the most essential things of the energy band diagram.
- We have used the potential energy barrier to understand motion of charge carriers. However, Fermi level can also be used for the analysis.
- The band diagram that contains only the variation of Fermi level along with charge carriers is called simplified band diagram.
- The electrons can be imagined to occupy the Fermi level on the top side and holes can be imagined to occupy the Fermi level on the bottom side.
- The **electrons want to reach lower levels** of Fermi energy whereas holes **want to reach higher levels** of Fermi energy.

Large forward current vs tiny reverse current

- Under biasing conditions, the electrodes of the battery change the Fermi levels of the p and n regions.
- Since the negative electrode supplies electrons, it raises the Fermi level of the connected region. Similarly, positive electrode lowers the Fermi level.
- Under forward biasing, the energy of electrons at n-region is raised. The flow of electrons to lower energy p-region is possible. Similarly, the energy of holes at p-region is lowered. The flow of holes to higher energy n-region is possible. This leads to **large forward current**.
- Under reverse biasing, the energy of electrons at n-region is lowered. The flow of electrons to higher energy p-region is difficult. Similarly, the energy of holes at p-region is raised. The flow of holes to lower energy p-region is difficult.
- However, the reverse bias is favourable for minority electrons in p region and minority holes in n-region. Since the number of these carriers is very few, we see a **tiny reverse current**.



Definition

Rectifying action of pn junction is its property to allow **uni-directional** conduction.

- The diode equation can be shown to be

$$I = I_s \left[\exp\left(\frac{eV}{k_B T} \right) - 1 \right]$$

  where I_s is the reverse saturation current.
- The equation and the $I - V$ capture the non-linear nature of p-n junction.
- In the forward bias condition, it acts as a "closed switch" allowing large current to flow through it.
- In the reverse bias condition, it acts as an "open switch" allowing insignificantly low current to flow through it.
- This unidirectional conduction is called rectifying action.

pn junction – Reverse Saturation Current

Definition

The drift current due to minority carriers is known as **reverse saturation current**.

- As the reverse bias increases in magnitude, the reverse bias current saturates to a constant and is given by

$$\begin{aligned}&\lim_{V\to-\infty} I_s\left[\exp\left(\frac{eV}{k_B T}\right)-1\right]\\&= I_s\left[\exp\left(-\infty\right)-1\right]\\&= I_s(0-1)\\&= -I_s\end{aligned}$$

- This saturation current in the reverse bias direction is called reverse saturation current.
- Since the minority carrier concentration does not depend on the bias and only depends on the temperature, it is a constant at a given temperature.

Electrical power

Definition

Power is defined as the rate change of work done per unit time.

- The mechanical power P_{mech} is given by

$$P_{\text{mech}} = \frac{\mathrm{d}W}{\mathrm{d}t} = \frac{\mathrm{d}Fs}{\mathrm{d}t}, \\ = F\frac{\mathrm{d}s}{\mathrm{d}t} = Fv.$$

Here F is the force applied along displacement s to do work $W = Fs$ on a particle moving with velocity v.

- The electrical power consumed along a resistor P_{elec} for one electron is given by $P_{\text{elec}} = Fv = -eEv_d$ where v_d is the drift velocity.
- The power consumed within a length L and area A of resistor with electron concentration n is $P_{\text{elec}} = -nLAeEv_d = -VjA = -VI$ where $V = El$ is the potential drop across the resistor an $I = jA$ is current across the resistor. Here we have used definition of current density $j = nev_d$.

pn junction – Power characteristics

Definition

The sign convention employed for power consumption is if the current direction is along the voltage drop, then power is consumed and if the current direction is opposite the voltage drop, then power is generated.

	R	B	pn
V_F	> 0	> 0	> 0
I_F	> 0	< 0	$\gg 0$
P_F	> 0	< 0	$\gg 0$
V_R	< 0	N.A.	< 0
I_R	< 0	N.A.	< 0
P_R	> 0	N.A.	> 0

- For the resistor, the current is always along the voltage drop, even if the voltage drop is reversed. Therefore, the power is consumed in both biases.
- For the battery, the current is opposite to the voltage drop, Therefore, power is generated in a battery.
- For the pn junction, the current is along the voltage drop in both cases. Therefore, the power is consumed in both biases. However, the magnitudes are different unlike resistor.

Conceptual Questions

Problem

What causes majority carriers to flow at the moment when p-region and n-region are brought together? Why does this flow not continue until all carriers have recombined? [Hint for second part: Convince yourself that the built-in electric field opposes the diffusion "forces" for both the electrons and holes.]

Tough problems

Problem

Prove that the analysis of pn junction using potential energy barrier maps with the analysis using Fermi energy level. In other words, prove that $E_{Fn} - E_{Fp} = eV_{ext}$.