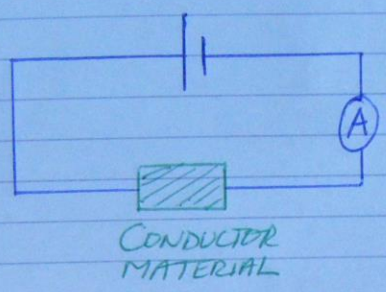
Semiconductors – B McMULLEN

This is a group of materials that lie between the extremes of conductors and Insulators.

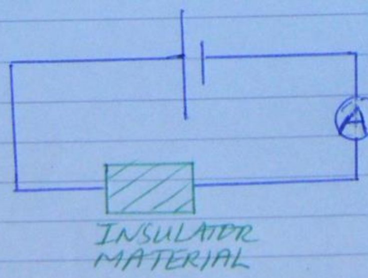
Conductors



Very Low Resistance

Conductors are typically metals (also carbon) and have a very low resistance.
∴ The current passing through a conductor is high.

Insulators

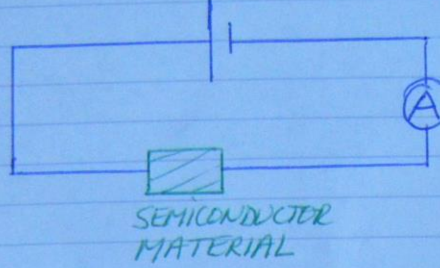


Extremely high Resistance

Insulators are typically non-metals and have an extremely high resistance.

∴ Current ≈ 0.

Semiconductors



High Resistance

Semiconductors can conduct electric current but at a much lower level than a conductor.

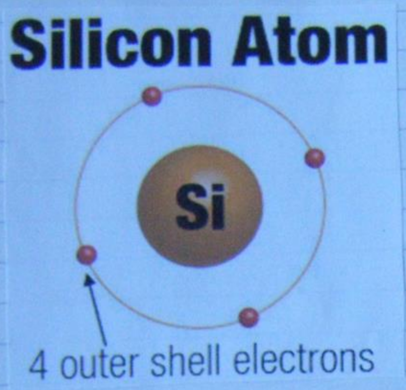
Typical materials are Silicon and Germanium.

The conduction of a semiconductor depends on how easily the outer electrons in the atom of a substance are removed from the atom.

Doping

This involves adding an impurity atom into a pure semiconductor material.

This will increase its current carrying capabilities by reducing its resistance.



Silicon has 4 valency electrons available for bonding with other atoms.

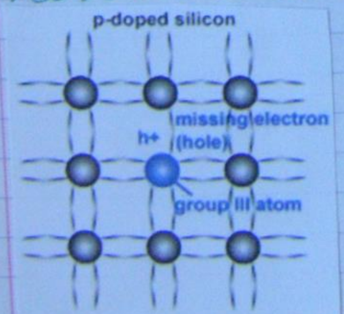
There are 2 types of doping:

- P-type where the majority of charge carriers are positive and are called holes.
- n-type where the majority of charge carriers are negative and are called electrons.

P - type doping

Silicon has 4 valency electrons that are available for bonding as mentioned previously.

If an impurity atom is added with 3 valency electrons then there is a hole created due to an incomplete bond.



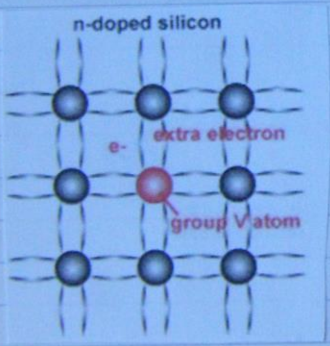
The missing hole can be clearly seen in the middle of the structure.

The hole moves through the semiconductor material giving an apparent flow of positive charge carriers.

The impurity atom here with 3 valency electrons is called an acceptor as it will accept an electron to increase the flow of current.

n-type doping

If an impurity atom is added with 5 valency electrons then there is an extra electron available to carry charge.



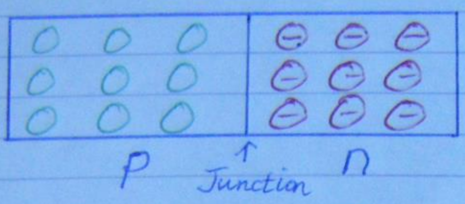
The impurity atom is called a donor as it will donate an extra electron to increase the flow of current.

(Four of these electrons fill up the valence band allowing the extra electron in the conduction band → see later)

Summary

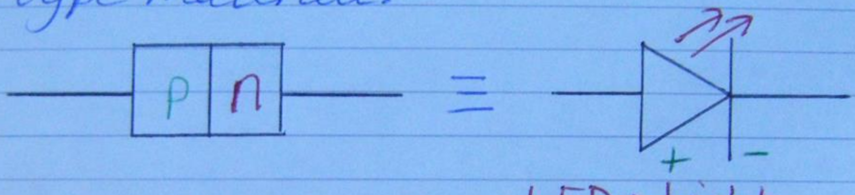
- Adding an impurity atom to a semiconductor material reduces the resistance of the material and therefore increases the current. $R\downarrow \therefore I\uparrow$
- p-type semiconductors → majority charge carriers are holes ie positive charge carriers.
- n-type semiconductors → majority charge carriers are electrons ie negative charge carriers.

p-n Junction



O → holes
⊖ → electrons

The p and n materials are both electrically neutral although they house the holes in the p-type material and the electrons in the n-type material.



LED → Light Emitting Diode

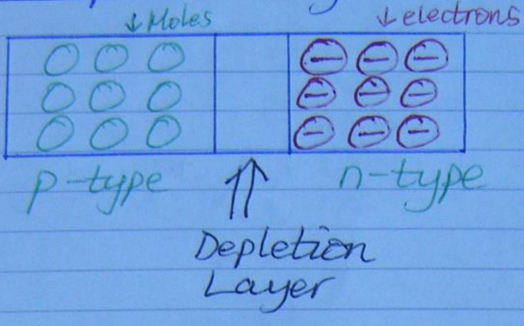
If electrons move across the junction from the n-type material to the p-type material then the p-type material will become negatively charged.

If holes move across the junction from the p-type material to the n-type material then the n-type material will become positively charged.

Conclusion

P and n-type are uncharged but they prefer the nature of their own charge carriers. ~~eg~~ electrons are preferred by the n-type material

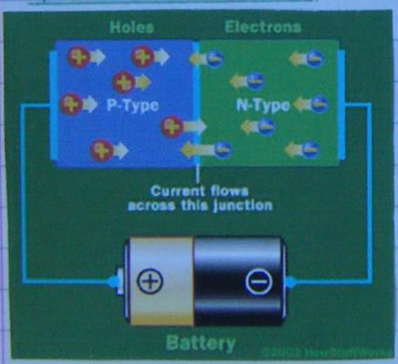
The depletion layer

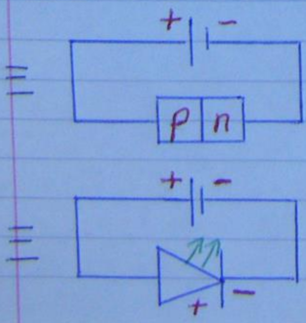


The depletion layer contains no charge. But unlike the p and n type material, they do not prefer the nature of either positive or negative charge carriers.

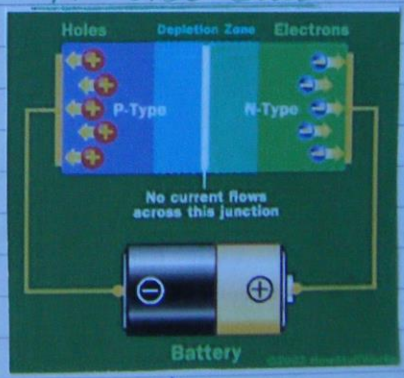
Bias.

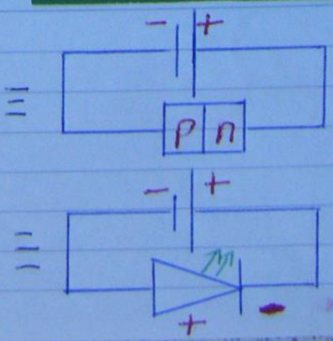
Forward Bias





Reverse Bias



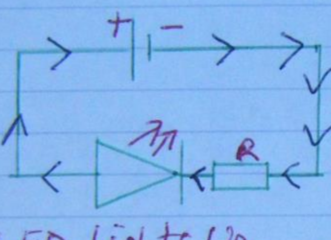


In NATS only the forward bias LED would light up.

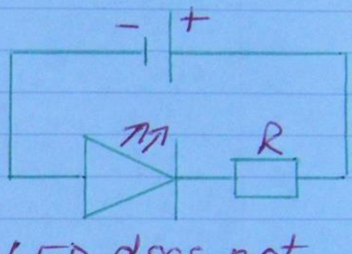
Why?

The negative side of the LED must be connected to the negative side of the battery.

eg



LED lights up.



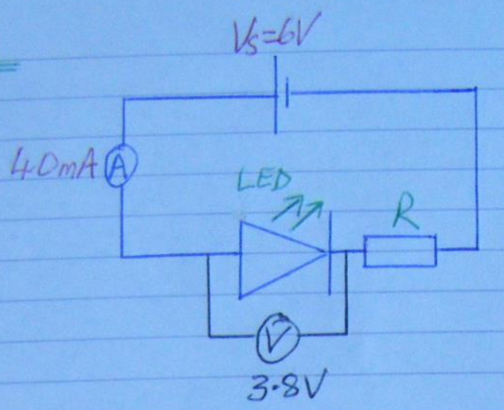
LED does not light up.

* The current (electron flow) only passes through the LED in one direction only. ie where the negative of the supply is connected to the negative side of the LED. *

In forward Bias (−ve charge carries) ⇒
- Flow of electrons
- $I \approx mA\ (\times 10^{-3} A)$
- Allows the LED to light up.

In Reverse Bias (+ve charge carriers) ⇒
- Hole flow
- $I \approx \mu A\ (\times 10^{-6} A)$
- The magnitude of the current is not sufficient to light up the LED.

Ex1



Q) a) What is the purpose of the resistor R in series with the LED?

b) Calculate the unknown resistance R when the voltage across the LED = 3·8V.

A) a) The resistor R is used to protect the LED from:

- Too high a current passing through the LED
  and
- Too high a voltage being dropped across the LED.

b) • $V_R = V_S - V_{LED} = 6V - 3{\cdot}8V = 2{\cdot}2V$

• $R = \frac{V_R}{I} = \frac{2{\cdot}2}{40 \times 10^{-3}} = 55\Omega$

* Usually LED's have resistors connected in series with them for the reasons given in a) above. However if a number of LED's are connected in series the resistor is * not needed. ie Voltage supply splits between LED's.

Diode – Bias Graphs

Reverse Bias
- Conduction of holes
- Current ≈ μA

ie $\times 10^{-9} A$

Forward Bias
- Conduction of electrons
- Current ≈ mA

ie $\times 10^{-3} A$

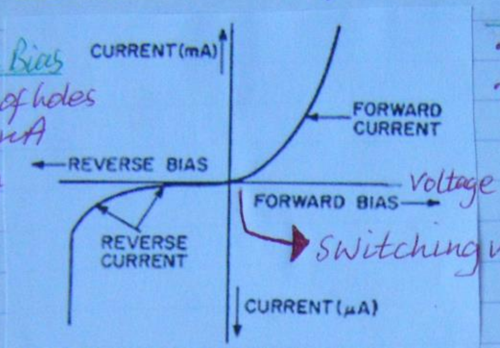
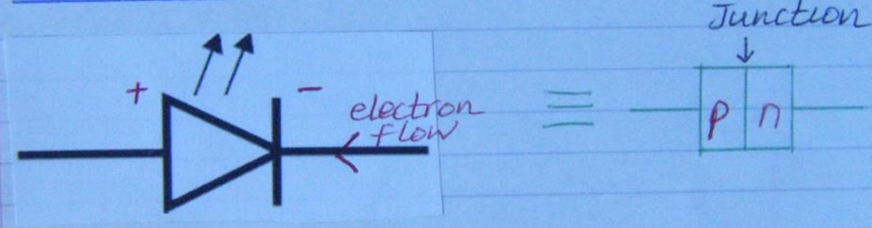


Figure 8. Voltage-current characteristic for a p-n junction.

The LED

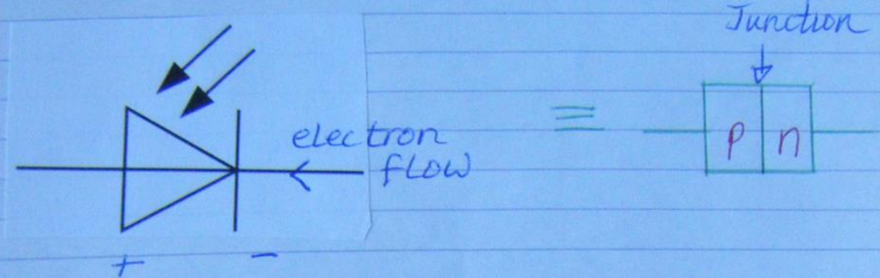


Electrons and holes pass across the p-n junction and recombine to form electron-hole pairs.

This allows photons to be given off in the form of light energy.

LED → **L**ight **E**mitting **D**iode

The Photodiode



A photodiode reacts to light by absorbing it.

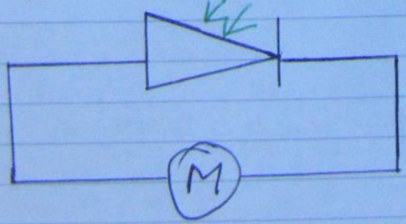
The photodiode can exist in two different modes.

- Photovoltaic Mode (≈ Solar Cell)
- Photoconductive Mode (≈ LDR → Light Dependant Resistor)

1) Photovoltaic Mode

The photodiode acts as a voltage supply.

ie There are no batteries or power supplies in the circuit with the photodiode.



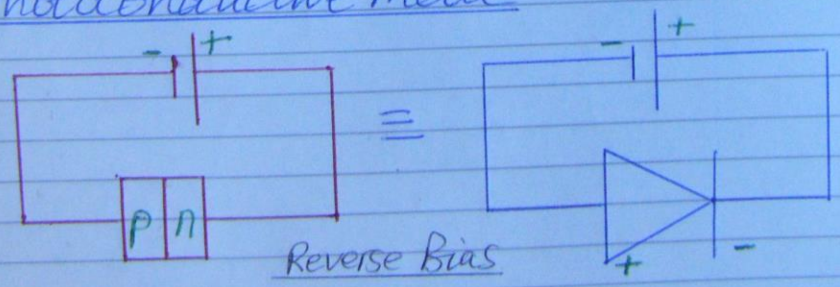
Energy change in the photodiode in this mode is Light → Electrical

- Here the photodiode acts as a voltage supply to provide the energy required to turn the electric motor.

- When light energy falls onto the photodiode they split up the electron-hole pairs at the junction to create free charge carriers. This results in a voltage being set up across the p-n junction. This voltage will operate and turn the electric motor in the circuit.

- If the Irradiance of the light hitting the photodiode increases then more photons of light will be absorbed at the junction per second. This will effectively increase the voltage of the supply and the electric motor will turn faster.

2) Photoconductive mode



As a voltage supply is present then the photodiode is connected in the photoconductive mode.

- As the light Irradiance increases on the photodiode then more photons of light are absorbed per second. Electron-hole pairs at the junction are split apart leading to free charge carriers in the depletion layer.

This production of free charge carriers reduces the resistance of the photodiode and allows a current to flow.

- As the light Irradiance ↑ ∴ Resistance of the photodiode ↓

- As the Resistance of the photodiode ↓ ∴ Current flow through the photodiode ↑

Light Irradiance ∝ Current flow

From the Inverse Square Law

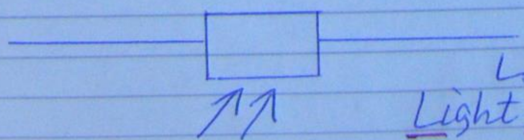
$$I_1 d_1^2 = I_2 d_2^2$$

where I stands for light Irradiance or Current

* As Light Irradiance ∝ Current *

In conclusion

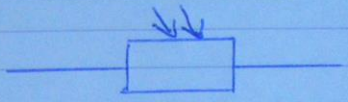
The photodiode in the photoconductive mode acts like an LDR.



LDR

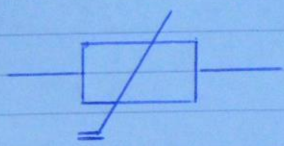
Light Dependant Resistor

For crashers!!

-  LDR <u>LURD</u>

Light Irradiance ↑ ∴ Resistance of the LDR ↓

<u>L</u>ight <u>U</u>p <u>R</u>esistance <u>D</u>own

-  Thermistor <u>TURD</u>

Temperature ↑ ∴ Resistance of the Thermistor ↓

<u>T</u>emperature <u>U</u>p <u>R</u>esistance <u>D</u>own

<u>Ex 2</u>

A sample of pure semiconductor material has a small quantity of impurity atoms added to form a p-type semiconductor.

Q// a) What is this process called?

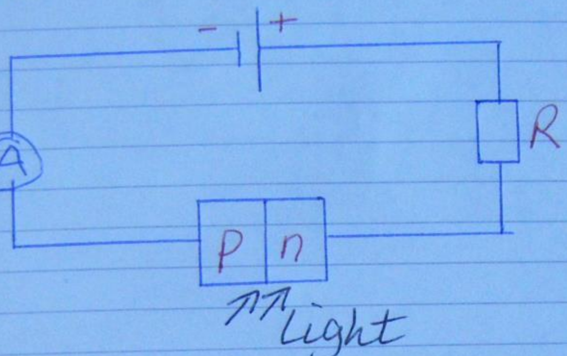
b) How does the addition of impurity atoms affect the resistance of the material?

A// a) Doping (p-type)

b) The resistance of the semiconductor material decreases, so the current passing through it will increase.

Ex3

A p-n junction is used as a photodiode and a voltage is applied across it as shown below.



Q a) In what mode is the photodiode operating?

A a) Photoconductive Mode.

Q b) State two reasons why you have chosen this mode.

A b)
- This circuit has a battery which you do not have in the photovoltaic mode
- The photodiode is connected in reverse bias.

Q c) i) The Irradiance of the light at the photodiode increases. Explain what happens to the current in the circuit.

A c) i)
- As the light Irradiance increases, then more photons are absorbed at the photodiode per second.

- More electron-hole pairs are split at the junction and this will increase the number of free charge carriers.
- As the number of free charge carriers increase then the current flow increases.

Q c) ii) If the lamp is switched on at a distance of 5 cm from the photodiode, then the current reading on the ammeter would be 18μA.
If the lamp is then moved to a distance of 15cm from the photodiode then calculate the new reading on the ammeter.

A c) ii) $I_1 d_1^2 = I_2 d_2^2$

$\Rightarrow 18 \times 10^{-6} \times (0.05)^2 = I_2 \times (0.15)^2$

$\Rightarrow 4.5 \times 10^{-8} = 0.0225 I_2 \Rightarrow I_2 = \frac{4.5 \times 10^{-8}}{0.0225}$

$\Rightarrow \underline{I_2 = 2 \times 10^{-6} A \ (2\mu A)}$

Q d) The sensitivity of a certain photodiode is greatest when each incident photon has an energy of 2.3×10^{-19} J.

Calculate the wavelength of these photons.

A d) $E = 2.3 \times 10^{-19} J$
$\lambda = ?$

2 stage calculation
- $E = hf$ then
- $v = f\lambda$

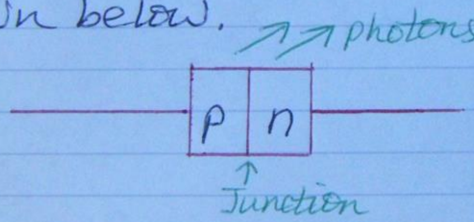
- $E = hf \Rightarrow f = \frac{E}{h} = \frac{2.3 \times 10^{-19}}{6.63 \times 10^{-34}} = \underline{\underline{3.47 \times 10^{14} Hz}}$

- $v = f\lambda \Rightarrow \lambda = \frac{v}{f} = \frac{3 \times 10^{8}}{3.47 \times 10^{14}} = \underline{\underline{8.65 \times 10^{-7} m}}$

($8.65 \times 10^{-7} m = 865 \times 10^{-9} m = 865 nm$ ∴ Outwith the visible spectrum)

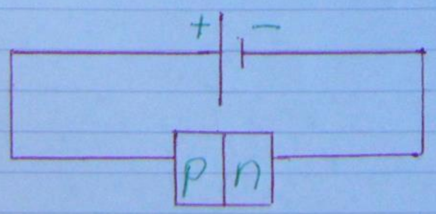
Ex4

An LED consists of a p-n junction as shown below.



Q a) Copy the diagram and add a battery so that the p-n junction is in forward bias.

A a)



Forward Bias.

Q b) Using the terms electron, holes and photons, explain how light is produced at the p-n junction of the LED.

A b) • Electrons and holes recombine at the p-n junction

• Electron-hole pairs are created

• This creates photons which are given off in the form of light energy.

Q c)i) The LED emits photons of energy 3.68×10^{-19} J.

Calculate the wavelength of a photon of light from this LED.

A c)i) • $E = hf \Rightarrow f = \frac{E}{h} = \frac{3.68 \times 10^{-19}}{6.63 \times 10^{-34}} = 5.55 \times 10^{14}$ Hz

• $v = f\lambda \Rightarrow \lambda = \frac{v}{f} = \frac{3 \times 10^{8}}{5.55 \times 10^{14}} = 5.4 \times 10^{-7}$ m

(5.4×10^{-7} m $= 540 \times 10^{-9}$ m $= 540$ nm $=$ GREEN)

Q c)ii) Calculate the minium potential difference across the p-n junction in c)i) when it emits photons.

A c)ii) $E_W = QV \Rightarrow V = \frac{E_W}{Q} = \frac{3.68 \times 10^{-19}}{1.6 \times 10^{-19}} = 2.3$ V

charge on an electron.

Band Theory explained!!

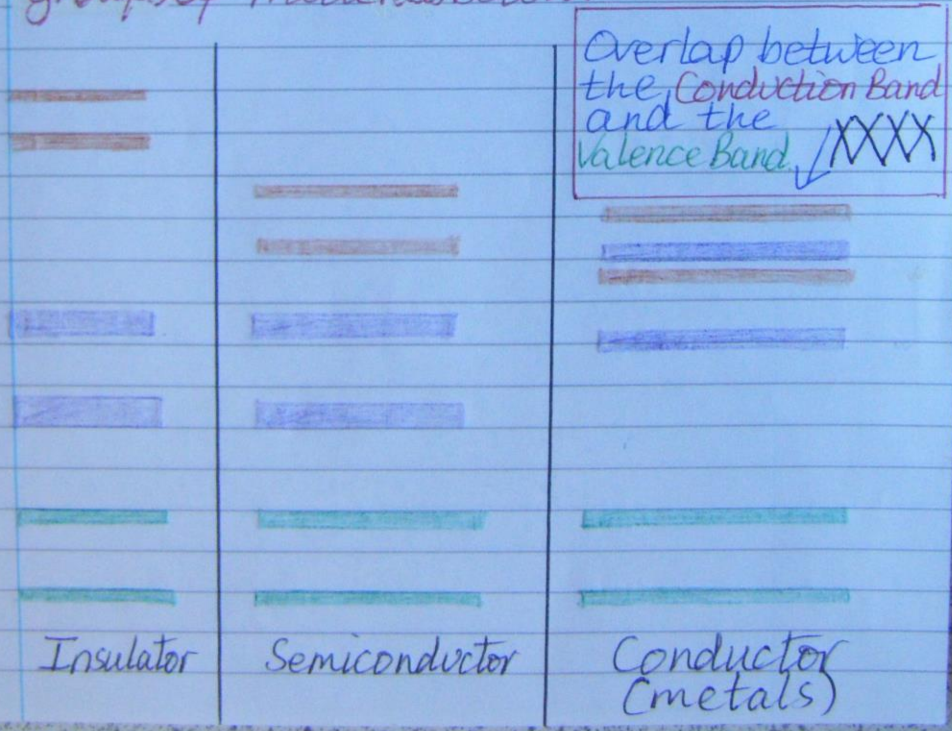
Conductors, semiconductors and insulators have differences which can be explained in terms of bands.

The names of the three bands are:

For electrons

- Filled Band → (Lowest energy band)
- Valence Band →
- Conduction Band → (Highest energy band)

These bands are shown for the three groups of materials below.



Conductors (metals)

The conduction band contains electrons but is not completely full. The valence band for a conductor is not filled and so the electrons can move through it. This shows that valence electrons are free to move. The valence band and the conduction band can overlap!!

Semiconductors

The gap between the valence band and the conduction band is much smaller than that of an insulator.

Some electrons can move from the valence band to the conduction band at room temperature. However the conductivity of the semiconductor will increase, as the temperature increases ⇒ the band gap decreases.

What is a Fermi Level?

An energy level where the probability of finding an electron is 50/50 ie equal probability of finding or not finding an electron.

The Fermi level is shown as a dashed line at a point between the conduction Band and the valence Band.

From the diagram it shows that the three energy bands are separated by gaps.

In insulators, semiconductors and conductors (metals) the filled band is completely full with electrons.

The difference between insulators, semiconductors and conductors (metals) can be seen clearly with the valence band and the conduction band.

Insulators

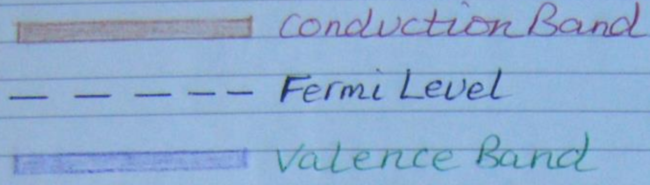
The valence band here is full of electrons but the band gap is too high between the valence band and the conduction band.

This means that the electrons would not have enough energy at room temperature to be able to jump up to the conduction band.

The conduction band will remain free of electrons in an insulator.

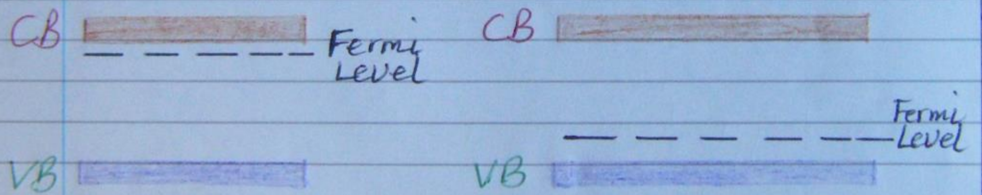
* Even if the temperature is increased the electrons would still not be able to jump from the valence band to the conduction band in an Insulator. *

Fermi Levels in Insulators and Semiconductors



The only difference between the Fermi level diagram for an Insulator and a semiconductor is that gap between the two bands is closer with a semiconductor.

Comparing the Fermi level in n-type and p-type semiconductors.

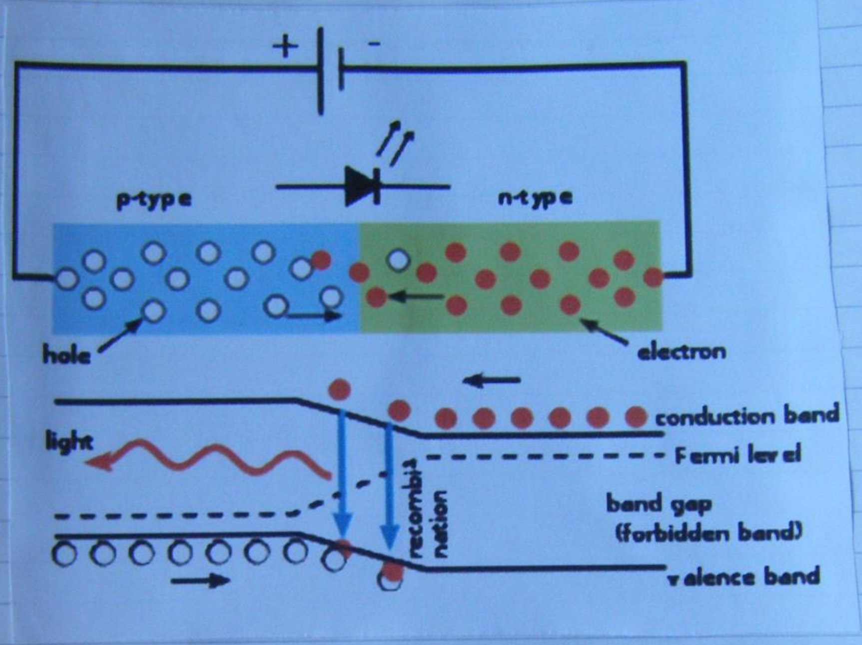


n-type p-type

n-type ⇒ The extra electron occupies levels closer to the Conduction Band.

p-type ⇒ The hole created by a missing electron moves the Fermi level closer to the Valence Band.

Using Band Theory to explain LED's



- The applied voltage causes the electrons to move away from the conduction band of the n-type towards the junction.

- The electrons then drop from the conduction band to the valence band.

- When an electron drops to the valence band a photon of light energy will be emitted.

* Electrons moving away from the n-type conduction band ≡ towards the p-type conduction band *