Higher Physics

Electricity

Summary Notes

- Monitoring and measuring a.c.
- Current, potential difference, power and resistance
- Electrical sources and internal resistance
- Capacitors
- Conductors, semiconductors and insulators
- p-n junctions

Monitoring and measuring a.c.

When electric charges move there is said to be an electric **current.**

Current is the rate of at which charge passes a point.

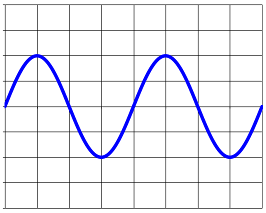
$$current = \frac{charge}{time} \qquad I = \frac{Q}{t}$$

Current is measured in **amperes** (A).

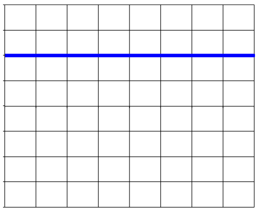
Direct current (**d.c.**) is when the current is always in one direction. Batteries supply d.c.

Alternating current (**a.c.**) is when the current changes direction every fraction of a section. The mains supply in the UK is a.c.

The difference between a.c. and d.c. can be observed by connecting the supplies to an oscilloscope.



a.c.

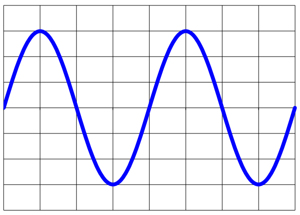


d.c.

In an a.c. supply the maximum voltage is called the **peak voltage**.

The frequency and peak voltage of an a.c. supply can be determined from an oscilloscope pattern.

e.g.



Timebase setting = 5·0 ms div^{-1}

Y-gain setting = 2·0 V div^{-1}

frequency:

$$\begin{aligned} period &= timebase\ setting \times number\ of\ divisions \\ &= 5\cdot0\ \text{ms div}^{-1} \times 4\ \text{div} \\ &= 20\ \text{ms} \\ frequency &= \frac{1}{period} \\ &= \frac{1}{20\times10^{-3}} \\ &= 50\ \text{Hz} \end{aligned}$$

peak voltage:

$$\begin{aligned} peak\ voltage &= Y\text{-}gain\ setting \times number\ of\ divisions \\ &= 2\cdot0\ \text{V div}^{-1} \times 3\ \text{div} \\ &= 6\cdot0\ \text{V} \end{aligned}$$

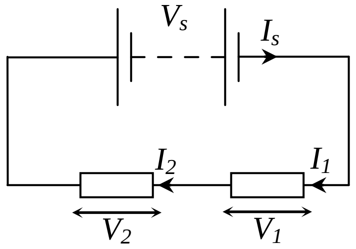
In an a.c. supply the values of current and voltage are continuously varying so the values usually quoted are the equivalent values of a d.c. supply that have the same effect. These are known as the **root mean square (r.m.s.)** values. (Note: the r.m.s. value is a kind of average value).

The peak value of the current or voltage an a.c. supply is greater than the r.m.s. value.

$$I_{peak} = \sqrt{2}\, I_{rms} \quad \text{and} \quad V_{peak} = \sqrt{2}\, V_{rms}$$

Current, potential difference, power and resistance

Series circuits



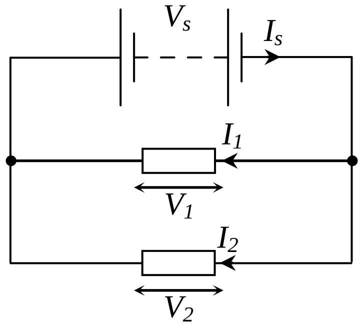
There is only one path for current in a series circuit, so the current is the same at all points.

$$I_S = I_1 = I_2 = \cdots$$

The sum of the voltages across components in series is equal to the supply voltage.

$$V_S = V_1 + V_2 + \cdots$$

Parallel circuits



In a parallel circuit the sum of the currents in each branch of the circuit is equal to the current in the supply.

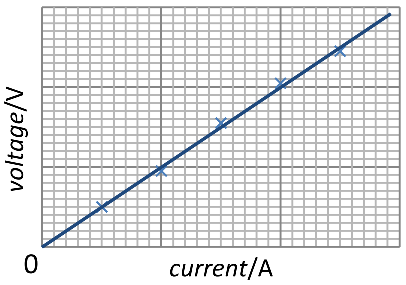
$$I_S = I_1 + I_2 + \cdots$$

The voltages across parallel branches in the circuit are the same.

$$V_S = V_1 = V_2 = \cdots$$

Resistance is the opposition to the movement of charge through a material. Increasing the resistance in an electrical circuit decreases the current.

Resistance is measured in **ohms** (Ω).



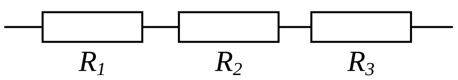
For a given resistor the ratio V/I remains approximately constant, provided there is no change in temperature (i.e. the graph of voltage against current is a best fit straight line through the origin).

This ratio is defined as the **resistance** of the resistor.

The relationship between resistance, current and voltage is known as **Ohm's Law**.

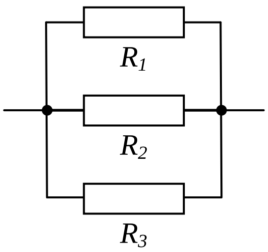
$$R = \frac{V}{I}$$

The total resistance of resistors connected in series is equal to the sum of the individual resistances.



$$R_T = R_1 + R_2 + \ldots$$

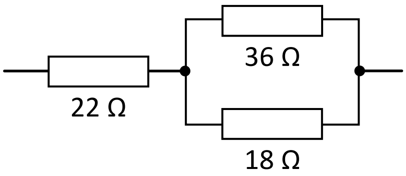
The total resistance of resistors connected in parallel is less than the smallest value of the individual resistors.



$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$$

Any combination of resistances can be reduced to a single equivalent resistance.

e.g.



38 Ω and 18 Ω in parallel: $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$

$= \frac{1}{36} + \frac{1}{18}$

$R_T = 12\ \Omega$

12 Ω and 22 Ω in series: $R_T = R_1 + R_2$

$= 22 + 12$

$= 34\ \Omega$

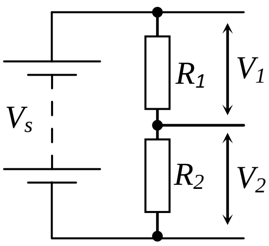
The **power** developed in a component can be determined by using the relationship:

$$P = IV$$

Alternatively, by combining this relationship with Ohm's Law we can also use

$$P = I^2R \quad \text{and} \quad P = \frac{V^2}{R}$$

A **potential divider** (voltage divider) circuit is made up of two (or more) resistors connected in series.



voltage divider circuit

In a potential divider circuit the supply voltage is shared (or divided) between the resistors.

The ratio of the voltages across the resistors in a potential divider is the same as the ratio of their resistances:

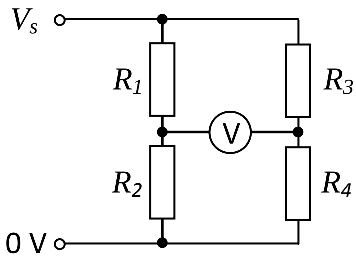
$$\frac{V_1}{V_2} = \frac{R_1}{R_2}$$

The voltage across a resistor in a potential divider can be calculated using:

$$V_1 = \left(\frac{R_1}{R_1 + R_2}\right) \times V_s$$

Additional information:

Two potential dividers connected in parallel is known as Wheatstone Bridge circuit. The voltage across a Wheatstone Bridge can be determined by calculating the voltage across each of the bottom resistors in the potential dividers and then calculating the difference between these two voltages.



$$V_2 = \frac{R_2}{R_1 + R_2} \times V_s$$

$$V_4 = \frac{R_4}{R_3 + R_4} \times V_s$$

Then: $V_{bridge} = V_2 - V_4$

Electrical sources and internal resistance

Electrical sources are devices that supply electrical energy (e.g. chemical cells, solar cells, thermocouples, dynamos and power supplies)

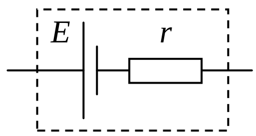
The **electromotive force** (e.m.f.) of a source is the electrical potential energy supplied per unit charge which passes through an electrical source. The SI unit of electromotive force is the volt (V).

The e.m.f. is the voltage measured across the source when it is **open circuit** (i.e. there is no current being drawn from the source).

When current is drawn from an electrical source some energy is wasted inside the source due to the resistance of the source itself, its **internal resistance**.

An **ideal source** is a source with no internal resistance.

A real electrical source can be considered as an ideal source with an e.m.f., E, in series with a small resistance, r.



The energy per unit charge that is wasted inside the electrical source is called the **lost volts**, V_{lost}.

$$V_{lost} = Ir$$

The energy per unit charge available at the terminals of the electrical source is called the **terminal potential difference**, V_{tpd}.

$$E = V_{tpd} + V_{lost}$$

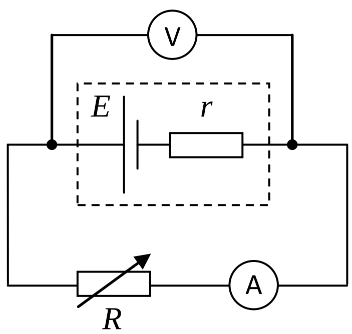
When an electrical source is connected to a load

$$V_{tpd} = IR_{load}$$

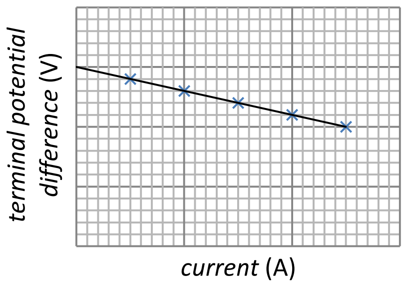
Combining these relationships gives:

$$E = V_{tpd} + Ir$$

The e.m.f. and internal resistance of a source can be determined using the following circuit.



The resistance of the variable resistor is altered to provide a variety of readings of terminal potential difference and current. A graph is then drawn of terminal potential difference against current.



Comparing the equation of the graph $y = mx + c$ to the relationship $V_{tpd} = E - Ir$ gives:

The e.m.f. is equal to the y-axis intercept

$$E = c$$

The internal resistance is equal to the negative of the gradient.

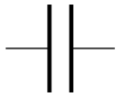
$$r = -m$$

When a cell is **short circuited** (i.e. the both the load resistance and terminal potential difference are zero) the entire e.m.f. is across the internal resistance and so the short circuit current is given by:

$$I_{short} = \frac{E}{r}$$

Capacitors

A **capacitor** is an electrical component that stores electrical charge.



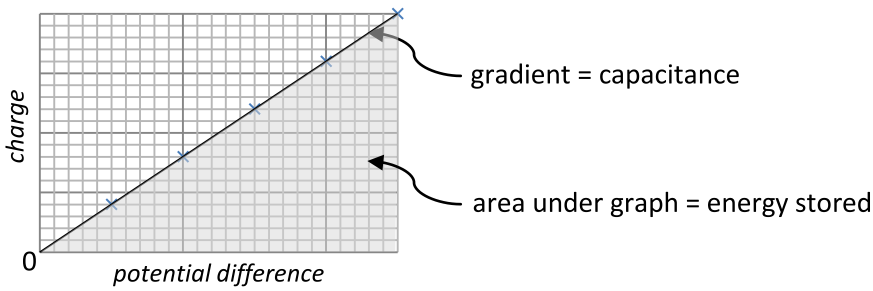
The **capacitance** C of a capacitor is the charge stored per volt of potential difference across it.

$$C = \frac{Q}{V}$$

The SI unit of capacitance is the farad (F). A one farad capacitor stores one coulomb of charge per volt of potential difference across it.

The capacitance of a capacitor can be determined experimentally by measuring the charge stored in the capacitor with a coulombmeter when the capacitor is charged to a variety of different potential differences.

A graph of charge against potential difference is then plotted and the capacitance is equal to the gradient of the graph.



Since capacitors can store charge they can also store energy. Energy is the product of charge and potential difference, therefore the energy stored in a capacitor can be determined from the area under the graph of charge against potential difference.

$$E = ½QV$$

(Note: This relationship is only true for capacitors where the potential difference across the capacitor changes as it charges, so the average potential difference is half of the maximum. In situations where there is a constant potential difference (e.g. from a cell or in an electric field) the energy transferred is given by the relationship $W=QV$.)

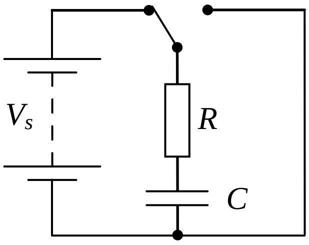
Combining this relationship with the relationship for capacitance also gives the alternatives:

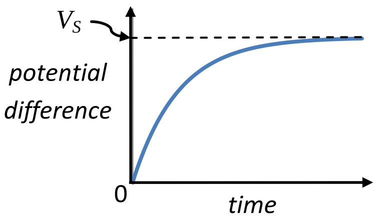
$$E = ½CV^2 \quad \text{and} \quad E = ½\frac{Q^2}{C}$$

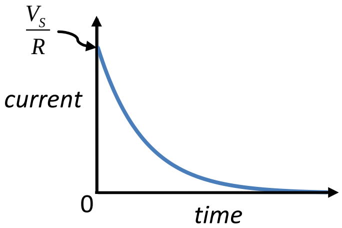
Capacitors can be used to store charge and therefore energy, e.g. in camera flashes and defibrillators. Capacitors can also be used to smooth d.c. supplies in power supplies and adapters.

When a capacitor is connected in series with a resistor it takes time to charge and discharge.

During **charging**, the potential difference across the capacitor increases up to a maximum value equal to the supply voltage, V_S, and the current decreases from an initial value of $\frac{V_S}{R}$.

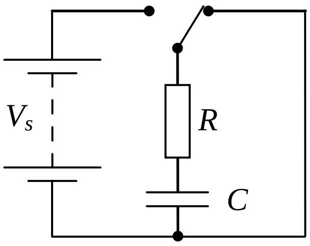


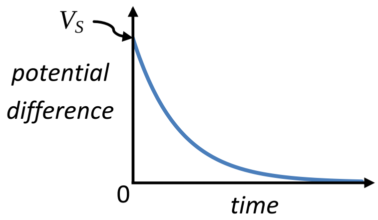


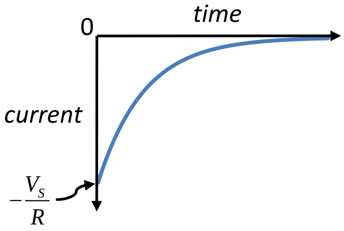


Note: These curves are exponential in shape – they start at a particular value and tend towards another value.

During **discharging** the potential difference across the capacitor decreases from the value it was charged to (i.e. V_S for a fully charged capacitor) and the current decreases from an initial value given by $-\frac{V_S}{R}$ (the value is negative because the current is in the opposite direction to that when it was charging)

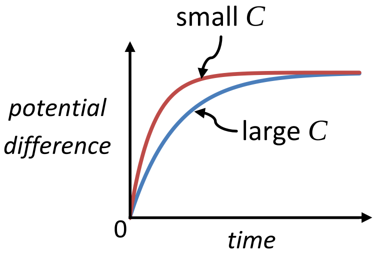


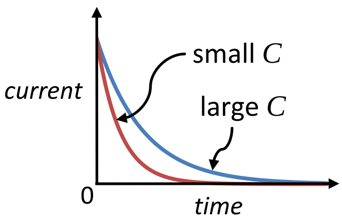




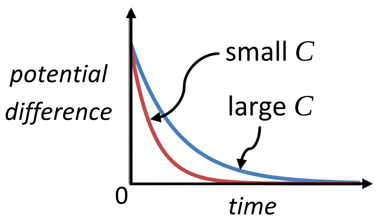
Increasing the capacitance C of the capacitor increases the time taken for the capacitor to charge/discharge.

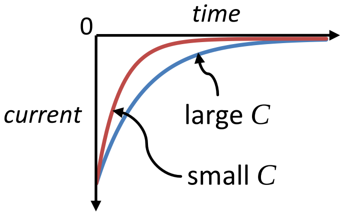
charging:





discharging:

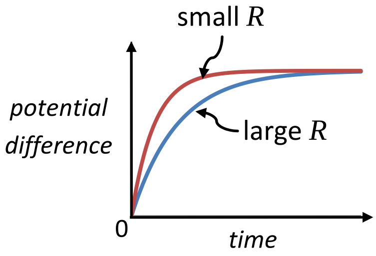


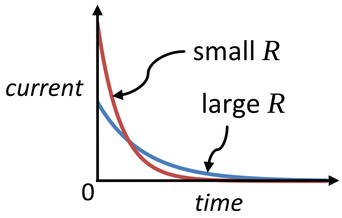


Note: The area under the current-time graph is equal to the charge stored by the capacitor and is therefore larger when C is larger.

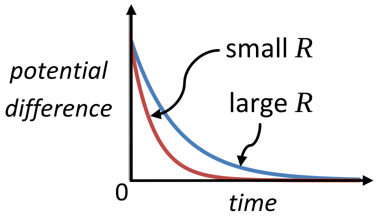
Increasing the resistance of the resistor also increases the time taken for the capacitor to charge/discharge.

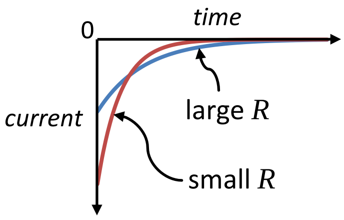
charging:





discharging:





Note: The area under the current-time graph is equal to the charge stored by the capacitor and is therefore the same when the capacitance is unchanged.

Conductors, semiconductors and insulators

According to their electrical properties, materials can be divided into three groups:

conductors: materials with many free electrons, which can easily move through the materials
e.g. metals and semi-metals such as graphite, antimony and arsenic

insulators: materials that have very few free electrons.
e.g. plastics, wood and glass

semiconductors: materials that are insulators when pure, but will conduct when an impurity is added or when they exposed to heat, light etc.
e.g. silicon, germanium, selenium and gallium arsenide

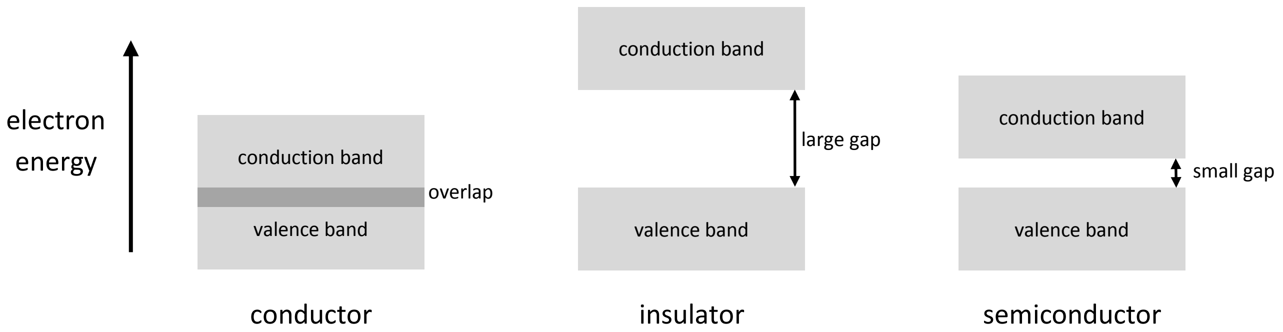
In order to explain the electrical properties of materials we can use **band theory**.

In isolated atoms, electrons occupy discrete energy levels (for further details see the Spectra topic in the Particles & Waves Unit). However, when atoms are brought together these energy levels interact with each other and become grouped into bands. These bands represent a continuous range of energies, but there are some groups of energy that are not allowed (band gaps). Generally, electrons will fill up the lower bands first.

In conductors, the highest occupied band is not completely full and this allows the electrons to move and therefore conduct. This band is known as the **conduction band**. The band below this (the **valence band**) is full and so does not allow the movements of electrons in it. However, at room temperature, the valence band actually overlaps with the conduction band and so this also assists with conduction.

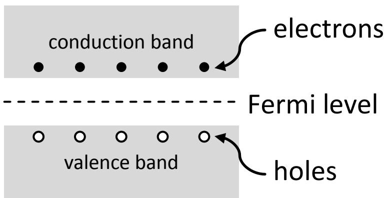
In an insulator, the highest occupied band (the valence band) is full. The first empty band above the valence band is the conduction band. For an insulator, the gap between the valence band and the conduction band is large and, at room temperature, there is not enough energy available to move electrons from the valence band into the conduction band where they would be able to contribute to conduction, so there is no electrical conduction in an insulator.

In a semiconductor, the gap between the valence band and conduction band is small and, at room temperature, there is sufficient energy available to move some electrons from the valence band into the conduction band, allowing some conduction to take place. This also leaves behind '**holes**' in the valence band, which allows further conduction to take place. These holes can be thought of as positive charges that can move. An increase in temperature increases the conductivity of a semiconductor.



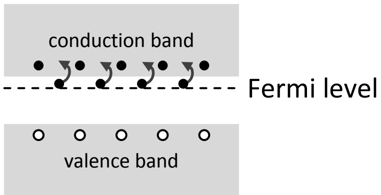
p-n junctions

The electrical properties of semiconductors can be altered by a process known as **doping**. Doping is the deliberate introduction of an impurity into a semiconductor. This can result one of two types of semiconductor; n-type or p-type.



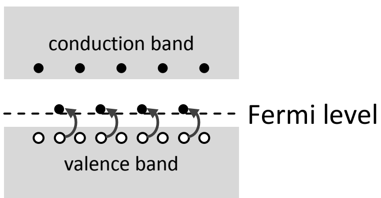
undoped (intrinsic)

In an undoped (intrinsic) semiconductor there are equal numbers of electrons in the conduction band and holes in the valence band, both of which contribute to conduction. This is represented by an energy level, known as the **Fermi level** that is positioned halfway between the valence band and conduction band. The Fermi level is the point where it is equally probable that an electron is or is not present.



n-type

In an **n-type** semiconductor an impurity is added (e.g. arsenic) which provides extra electrons to the semiconductor structure. These extra electrons are able to occupy energy levels close to the conduction band (donor levels) and are therefore easily excited into the conduction band. This is represented on an energy diagram as a movement of the Fermi level towards the conduction band. At room temperature there are therefore more electrons in the conduction band than holes in the valence band. This is known as n-type because the majority of charge carriers are negative (electrons).

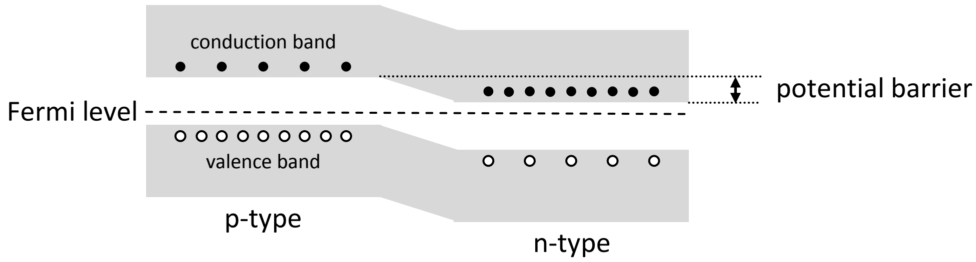


p-type

In a **p-type** semiconductor an impurity is added (e.g. indium) which has less electrons than the rest of the semiconductor. The missing electrons can be thought of as gaps at energy levels just above the valence band (acceptor levels) that electrons can move into. Electrons from the valence band are therefore easily excited into these levels, leaving behind additional holes in the valence band. This is represented on an energy diagram as a movement of the Fermi level towards the valence band. At room temperature there are therefore more holes in the valence band than electrons in the conduction band. This is known as p-type because the majority of charge carriers are positive (holes).

When the two different types of semiconductor are placed in contact with each other a layer, known as a **p-n junction,** is formed. The electrical properties of p-n junctions are used in a range of devices, such as solar cells, diodes and light emitting diodes.

In the absence of any external voltage (unbiased) the Fermi level is flat across the junction. The consequence of this is that in order for electrons to cross the junction from n-type to p-type they must have sufficient energy to move against the potential difference that is set up by the difference in the energy level of the conduction band (and valence band) between the two sides of the junction. This called the potential barrier.



In a **solar cell,** when photons of light with sufficient energy are incident on the junction they are able to give electrons enough energy to move from the valence band to the conduction band. This produces additional charge carriers in the junction, which are then able to cross the junction. The creation of these charge carriers means that a potential difference is maintained across the junction, even when a current is drawn. This is known as the **photovoltaic effect**.

When the p-type side of the junction is at a positive potential compared to the n-type the p-n junction is said to be **forward biased**. In this situation, if the potential difference is sufficiently large, electrons (and holes) can gain enough energy to cross the potential barrier and therefore the junction conducts.

When the n-type side of the junction is at a positive potential compared to the p-type the p-n junction is said to be **reverse biased**. In this situation, applying a potential difference to the junction increases the potential barrier so electrons (and holes) are unable to cross the potential barrier and therefore the junction will not conduct

A **diode** is a p-n junction that conducts when it is forward biased and does not conduct when it is reverse biased.

An **LED** is also a p-n junction that conducts when it is forward biased. In an LED, some electrons ‘fall’ from the conduction band into the valence band of the p-type semiconductor releasing their energy in the form of a photon of light.