Cumbernauld Academy
Physics Department

Unit 2 Electricity

Summary Notes

Electrons and Energy

Monitoring and measuring alternating current

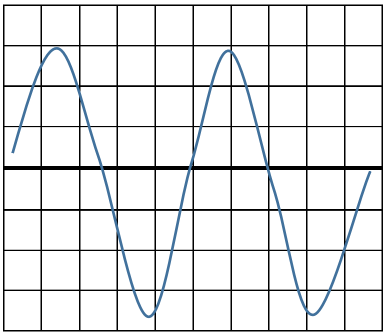
Alternating Current

Alternating Current (a.c.) is the a type of electric current that periodically _changes direction_. The electrons flow in one direction before changing to flow in the _opposite_ direction.

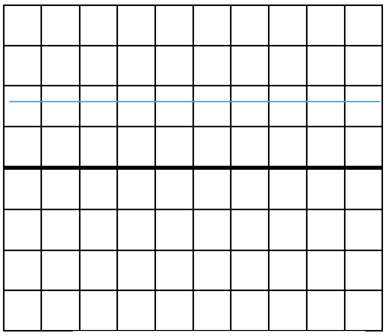
Direct Current (d.c.) is current that flows in _one direction_ only.

By using an oscilloscope we can see how the _voltage_ of an electric source varies with time. The voltage is plotted on the _y-axis_ and the time is plotted on the _x-axis_.

The following diagrams show each type of current displayed on an oscilloscope screen.



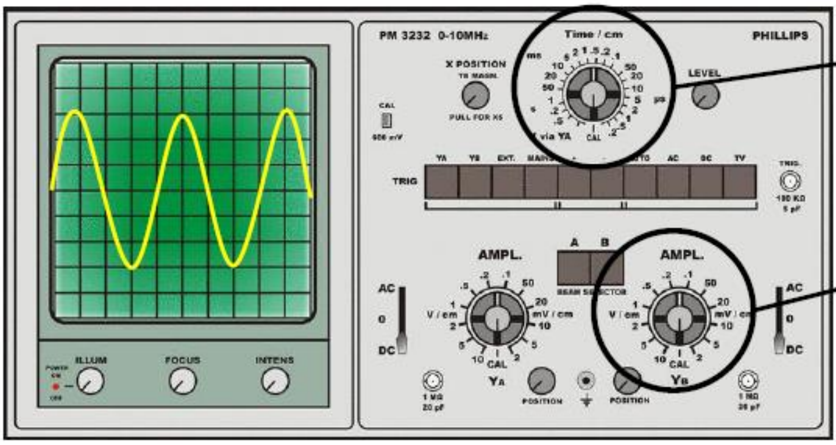
a.c. waveform



d.c. waveform

Measuring frequency and peak voltage

The values for voltage and time on an oscilloscope can be read from the number of divisions on the screen multiplied by the scale shown on one of two dials on the control panel at the side of the screen.



Time-base – this controls the time setting

Y-gain – this controls the voltage setting

Each division (box) on the screen is worth a different amount. The voltage scale (or y-axis) is often measured in volts/div. The time base (or x-axis) is measured in multiples of seconds/div.

We measure the **frequency** of the wave from its period – where the period of the wave is the _time_ it takes for a wave to pass a _point_.

$$f = \frac{1}{T}$$

We measure the peak voltage of a wave by finding the maximum positive value from the centre of the wave. This can be easily obtained by finding the difference between maximum value (the peak)and the minimum value (the trough) and diving by two.

$$V_{peak} = \frac{Volts\ between\ \max\ and\ minimum\ value}{2}$$

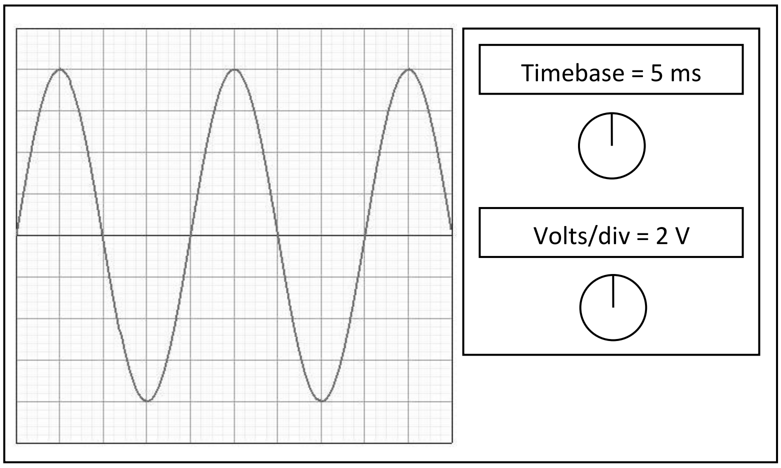
Example

Calculate:

(i) the frequency and

(ii) the peak voltage of the waveform shown on the CRO screen below.

Each box on the CRO screen has a side of length 1 cm.



(i) Frequency:

The distance between crests is 4 cm.

The time base is set at 5 ms cm^{-1},

Period, T = 4 × 5 ms = 4 × 0.005 = 0.02 s

$f = \frac{1}{T} = \frac{1}{0.02}$ = <u>50 Hz</u>

(ii) Peak Voltage:

The distance from bottom to top is 8 cm.

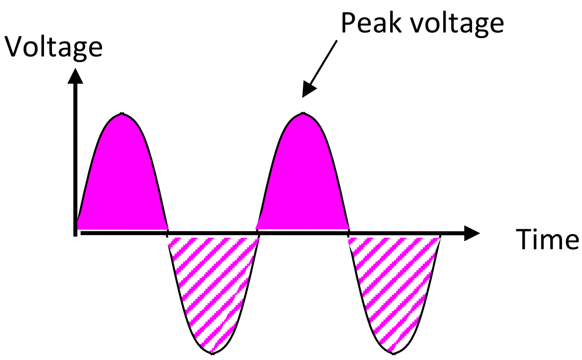
The volts/div is set at 2 V cm^{-1},

V_{peak} = ½ × 8 × 2

V_{peak} = <u>8 V</u>

Alternating current – peak and rms

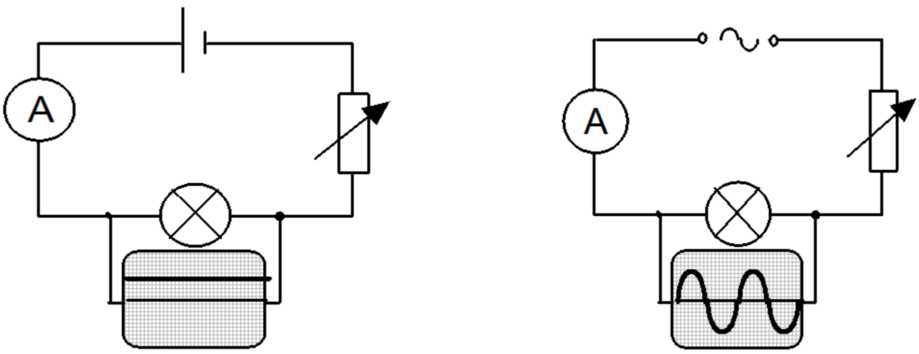
To calculate the average energy transferred b an a.c. current, we must take an average. Because alternating current is a sine wave, there is an equal number of peaks above and below the centre line – therefore the average would be zero. Therefore we are required to use a difference value for the 'average', known as the root mean square (or rms value).



The rms voltage (V_{rms}) is defined as the value of direct voltage that produces the same voltage as the alternating voltage.

The rms voltage is what is quoted on a power supply so a fair comparison between a.c. and d.c. can be made. E.g. a 6V battery (d.c.) will transfer the same energy to a bulb as a 6V rms a.c. supply.

Consider the following two circuits, which contain identical lamps.



d.c. voltage a.c. voltage

The variable resistors are altered until the lamps are of equal brightness, therefore both supplies are providing the same power to the lamp. If we use an oscilloscope to view the voltage traces, we can determine a relationship between the rms and peak voltages.

$$V_{peak} = \sqrt{2}V_{rms}$$

As V=IR, we can also develop a relationship for rms and peak current.

$$I_{peak} = \sqrt{2}I_{rms}$$

Example

A transformer is labelled with a primary coil of 230 V_{rms} and a secondary coil of 12 V_{rms}. What is the peak voltage which would occur in the secondary?

$V_{peak} = \sqrt{2} \times V_{rms}$

$V_{peak} = 1.41 \times 12$

$V_{peak} = \underline{17.0 \text{ V}}$

Current, voltage, power and resistance

Basic definitions

Current (I) is defined as the number of _Coulombs of charge_ to pass a point in _1 second_, or:

$$Q = It$$

Voltage (V) is the _energy transferred_ per unit of _charge_, or:

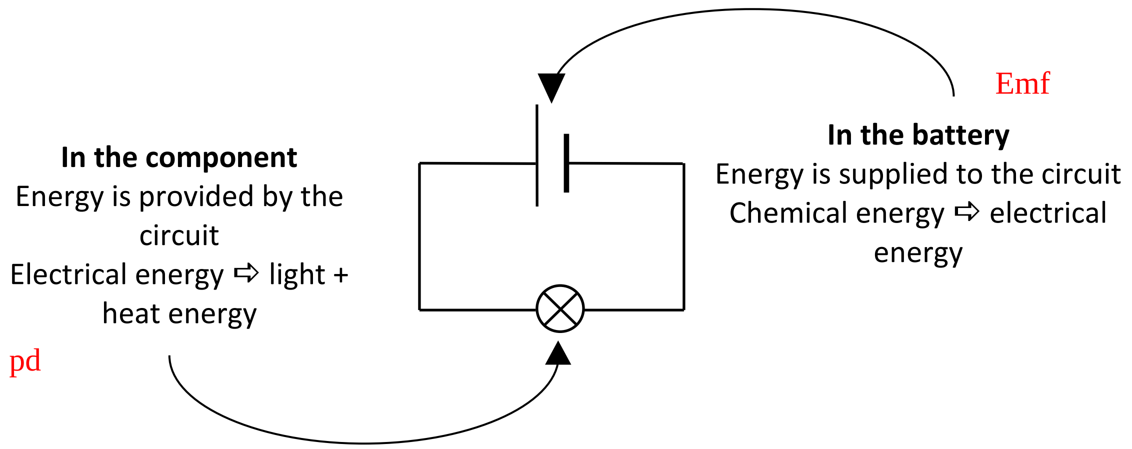
$$V = \frac{W}{Q}$$

Where W is the _work done_, i.e. the energy transferred. Therefore:

$$1\ volt\ (V) = 1\ joule\ per\ coulomb\ (J\ C^{-1})$$

When energy is being transferred from an external source to the circuit, the voltage is referred to as an _electromotive force (emf)_

When energy is transformed into another form of energy by a component in the circuit, the voltage is referred to as the _potential difference (pd)_



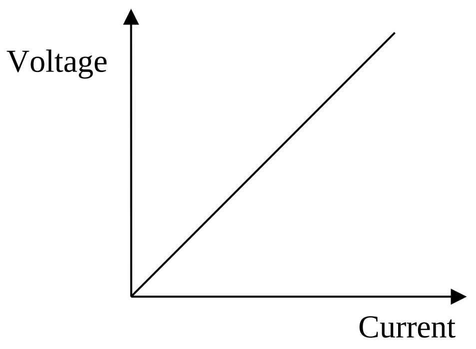
Sources of emf

Electromotive Force can be generated in a variety of ways:

Chemical cell	_Chemical_ energy drives the current (eg battery)
Thermocouple	_Heat_ energy drives the current (eg temperature sensor in an oven)
Piezo-electric generator	_Mechanical_ vibrations drive the current (eg acoustic guitar pickup)
Solar cell	_Light_ energy drives the current (eg solar panels on a house)
Electromagnetic generator	Changes in _magnetic field_ drive the current (eg power stations)

Ohm's Law

In a circuit with constant resistance, increasing the _potential difference (V)_ across a component causes the _current (I)_ passing through the component to _increase_ in direct proportion.



The gradient of this graph is a constant value.

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

This constant is equal to the resistance, R across the component.

$$R = \frac{V}{I} \quad or \quad V = IR$$

If a component has a _constant_ resistance as current through it is increased, it is said to be _ohmic_

If a component does **not** have a constant resistance as current increases through a component, it is said to be _non-ohmic_. Examples of non-ohmic components include _lightbulbs, transistors or diodes_.

For a non-ohmic component a V-I graph would be a _curved_ line (changing gradient).

Circuit Rules

A series circuit has _one_ path for the current to take around the circuit.

A parallel circuit has _multiple_ paths for the current to take around the circuit.

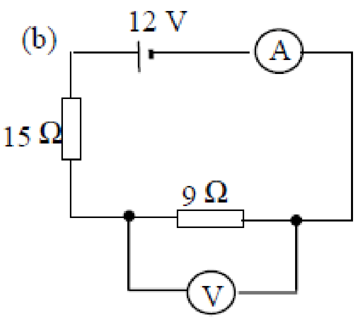
The circuit rules for series and parallel circuits are summarised below:

	Series	**Parallel**
Current	$I_S = I_1 = I_2 = I_3$	$I_S = I_1 + I_2 + I_3$
Voltage	$V_S = V_1 + V_2 + V_3$	$V_S = V_1 = V_2 = V_3$
Resistance	$R_T = R_1 = R_2 = R_3$	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$

where V_S = _supply voltage_, I_S = _current from the supply_ and R_T = _total resistance_

Examples:

1. Find the readings on the meters in the following circuit.



Step 1: Calculate the total resistance in the circuit

$R_T = R_1 + R_2 = 15 + 9 =$ 24 Ω

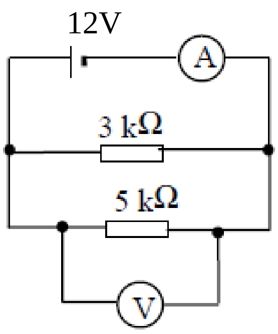
Step 2: Calculate current

I = V / R = 12/24 = 0.5 A

Step 3: Calculate the voltage across the 9 Ω resistor

V = IR = 0.5 x 9 = 4.5 V

2. Find the readings on the meters in the following circuit.



Step 1: Calculate the total resistance the circuit.

$1/R_T = 1/R_1 + 1/R_2 = 1/3 + 1/5 = 8/15$

$R_T =$ 1.9 kΩ

Step 2: Calculate current

I = V/R = 12/1.9 = 6.31mA

Electric Power

Power is the _electrical energy_ transferred in _one second_.

$$Power = \frac{Work\ Done}{Time} = \frac{QV}{t} = \frac{Q}{t} \times V = IV$$

Therefore,

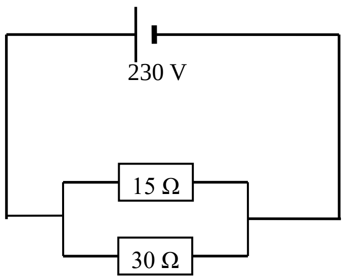
$$P = IV$$

From Ohm's Law, $V = IR$ and $I = \frac{V}{R}$

Substituting, $P = I \times IR$ and $P = \frac{V}{R} \times V$

Therefore, $P = I^2R$ and $P = \frac{V^2}{R}$

Example: An electric heater has two heating elements allowing three settings: low, medium and high. Show by calculation which element(s) would be switched on to provide each power setting.



For 30 Ω: $P = \frac{V^2}{R} = \frac{230^2}{30}$ = 1800 W → low power

For 15 Ω: $P = \frac{V^2}{R} = \frac{230^2}{15}$ = 3500 W → medium power

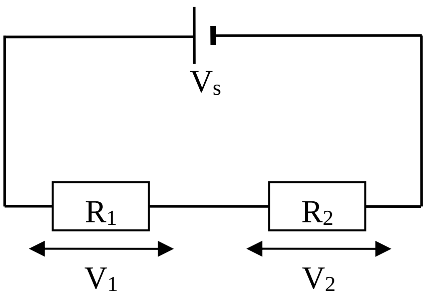
Combined resistance: $\frac{1}{R_T} = \frac{1}{15} + \frac{1}{30} = \frac{1}{10}$ => R_T = 10 Ω

For both: $P = \frac{V^2}{R} = \frac{230^2}{10}$ = 5300 W → high power

The potential divider

A potential divider consists of two electrical components (normally resistors) in series. This causes the voltage (or potential) to be split between them.

Consider the following:



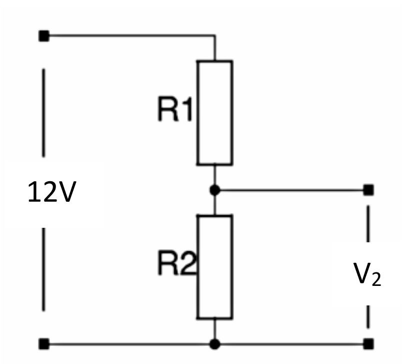
For a circuit such as this we have two equations we can use:

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

or

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

Example 1



A circuit is set up as shown, with R_1 = 300Ω and R_2 = 900Ω.

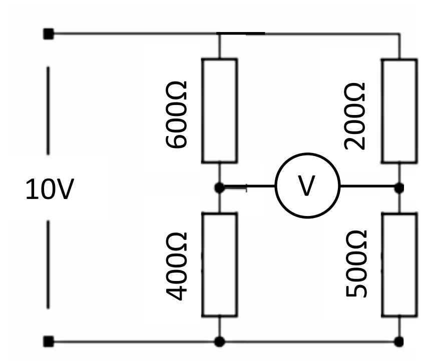
a) Calculate V_2.

b) If both resistors were replaced by 600Ω resistors, what would be the reading V_2?

a) $V_2 = \frac{R_2}{R_1 R_2} V_s$ $\quad V_2 = \frac{900}{1200} x12 = 9\text{V}$

b) $V_2 = 6V$, as both resistors are equal, they would both have an equal share of the voltage

Example 2 - Wheatstone Bridge



a) Calculate the reading on the voltmeter.
b) In what scenario would the reading on the voltmeter be zero?

a) First you need to calculate the potential on either side of the voltmeter

$V_2 = \frac{R_2}{R_1 R_2} V_s = \frac{400}{1000}\ x\ 10$ = 4V

$V_2 = \frac{R_2}{R_1 R_2} V_s = \frac{500}{700}\ x\ 10$ = 7.1V

Reading on voltmeter is difference between these

V = 7.1 – 4 = 3.1V

b) The voltmeter reading would be zero when the potential on either side of the bridge is the same – i.e. the ratio of resistors on either side is the same.

Electrical Sources and Internal Resistance

Internal Resistance

Until now, we have assumed all power supplies have been ideal. This means that their voltage would remain constant and that they can supply any current as long as they are connected to the correct resistance.

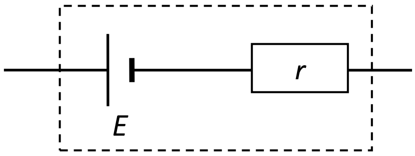
However, the battery itself has a resistance, which we call the **internal resistance, r**. Energy is used up in overcoming the internal resistance of the supply, so the terminal potential difference (tpd) will be reduced.

$$tpd = the\ energy\ per\ unit\ charge\ available\ at\ the\ output\ of\ the\ battery$$

This energy per unit charge lost in overcoming the internal resistance is known as the lost volts, where:

$$Lost\ volts\ = Ir$$

We can think of a real power supply or battery as having two parts – a source of electrical energy (E) and an internal resistor (r).



Real cell

Emf, tpd and 'lost volts'

1. **Open Circuit (*I*=0)**

To find the voltage of an ideal cell (no energy loss from internal resistance) we use an open circuit. This voltage is called the **electromotive force, or emf**.

$$emf\ = energy\ supplied\ to\ each\ coloumb\ of\ charge\ passsing\ through\ the\ supply$$

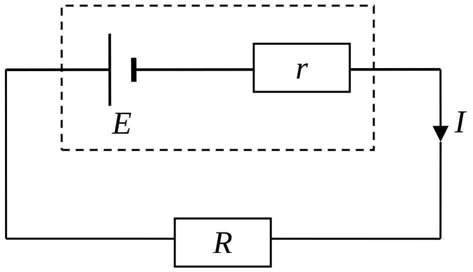
An open circuit is one in which there is no current flowing. We can measure the emf by connecting a voltmeter or oscilloscope across the supply when there is an open circuit.

This can be explained by considering the diagram above. We know that lost volts = Ir. If there is no current in the circuit, the lost volts will be zero. Therefore there is no voltage drop across the cell, and a voltmeter would register the emf of the battery.

2. Under load

When a cell is connected in a circuit, the **external resistance R** can be referred to as the load resistance.

If we apply Ohm's Law to a circuit containing a battery of emf E, and internal resistance r with an external load resistance R:



$$emf = tpd + lost\ volts$$

$$E = V_R + V_r$$

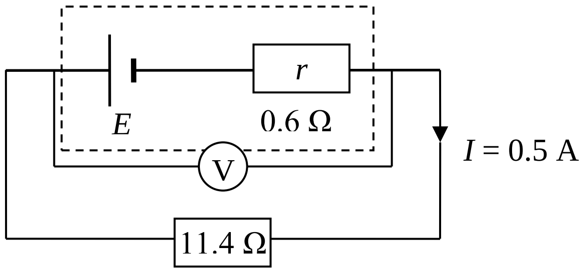
$$E = V + Ir$$

We can also express this equation in the following, as V = IR,

$$E = IR + Ir \qquad or \qquad E = I(R + r)$$

Example

Consider the case of a cell with an internal resistance of 0.6 Ω delivering current to an external resistance of 11.4 Ω:



Calculate the tpd of the cell:

$V = IR$ = 0.5 × 11.4 = <u>5.7 V</u>

Calculate the lost volts:

Lost volts = Ir = 0.5 x 0.6 = 0.3V

State the emf of the cell:

Emf = tpd + lost volts = 5.7V +0.3V = 6V

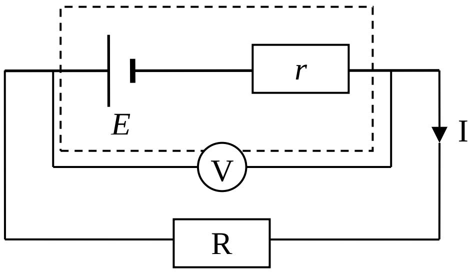
3. Short Circuit (R = 0)

The maximum current that can pass through a circuit is known as the short-circuit current. This is the current that will flow when the terminals of the supply are connected by a short piece of thick wire (no external resistance). As R = 0, we get the following relationship:

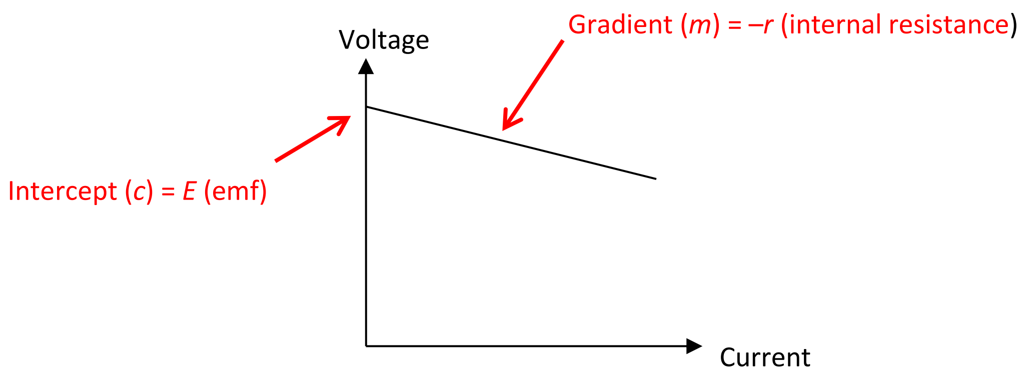
$$E = Ir$$

Measuring E and r by graphical methods

When we increase the current in a circuit like the one shown below, the energy lost in the supply due to heating will increase. Therefore, the 'lost volts' will increase and the tpd will decrease.



If we plot a graph of ***V* on the *y*-axis against *I* on the *x*-axis**, we get a straight line of negative gradient.



$$emf\ (E) = y - intercept$$

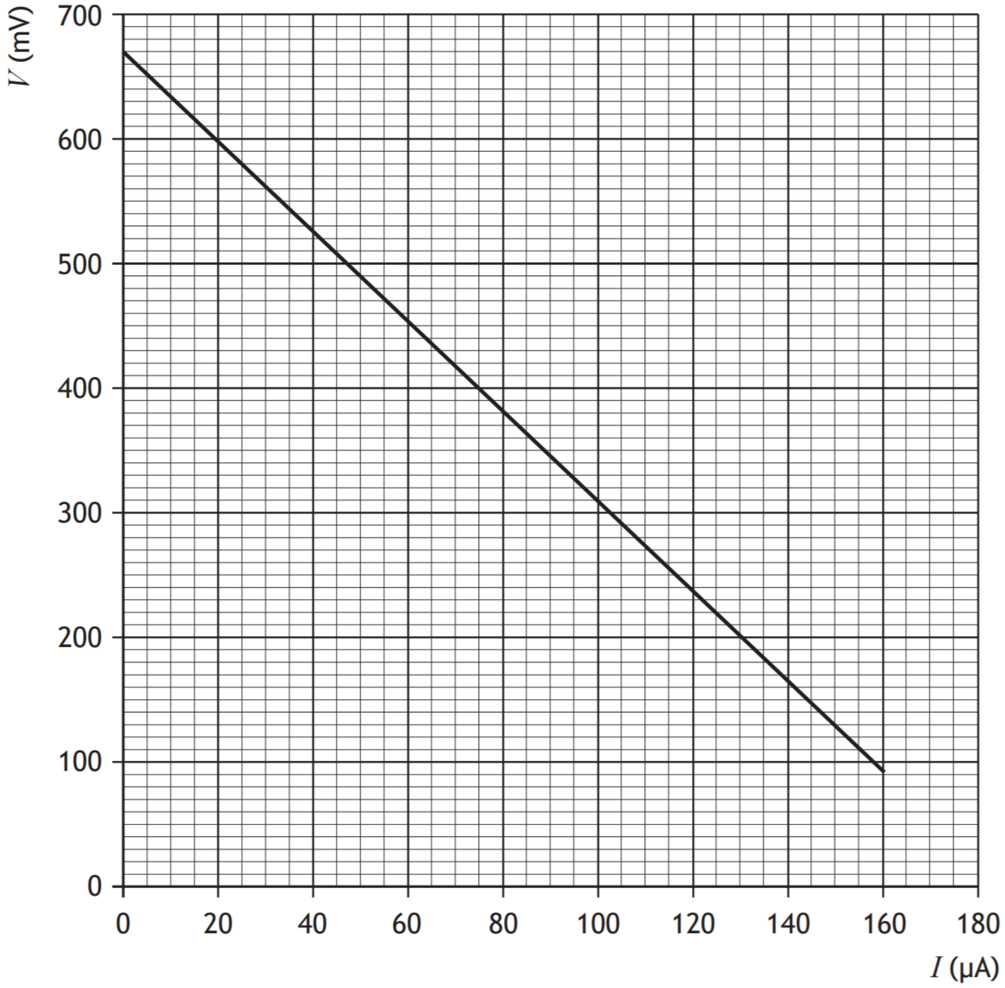
$$Internal\ resistance\ (r) = \ - gradient$$

$$Short\ circuit\ current = x - intercept$$

Where emf can be found when I=0, and short circuit current when tpd (V) = 0.

Worked example (2018 Q11b)

The student uses readings of current I and terminal potential difference V from this circuit to produce the graph shown.



a) Determine the internal resistance of the battery.
b) State the emf of the battery

a) $gradient = \frac{(290\ x\ 10^{-3} - 470\ x 10^{-3})}{(105\ x\ 10^{-6} - 55 x 10^{-6})}$

$$gradient = -3600$$

$$gradient\ = -r$$

$$r = 3600\Omega$$

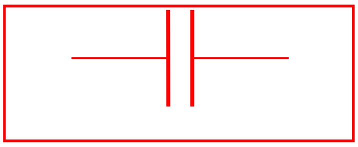
b) Emf = y-intercept
Emf = 670mV

Capacitors

Capacitance

Capacitance is the ability of a component to store charge. A device that stores charge is called a _**capacitor**_. It is measured in units of _Farads (F)_.

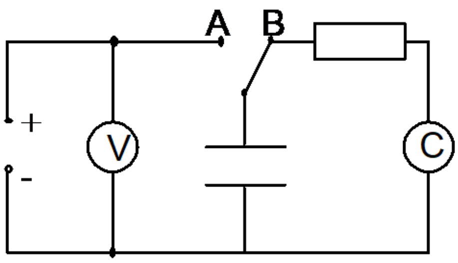
Capacitors consist of two conducting layers separated by an insulator. The circuit symbol for a capacitor is:



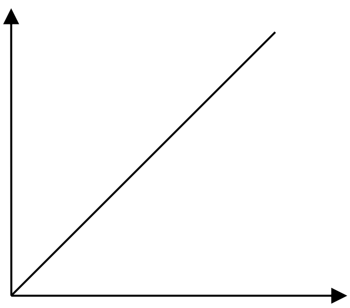
When a capacitor is charging, the current is not constant. This means that Q=It **cannot** be used to calculate the charge stored in a capacitor.

Relationship between charge and pd

A capacitor is charged to a chosen voltage by setting the switch to A. The charge stored can be measured directly by discharging through the coulomb meter by moving the switch to B.



In this way pairs of readings of voltage and charge are obtained. When a graph of charge stored on the capacitor is plotted against the pd (voltage), it is found that the charge is directly proportional to the pd (voltage) across it:



From the graph:

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

This constant is defined as the Capacitance, C:

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

From this equation, we get the definition for capacitance:

$$Capacitance = charge\ stored\ per\ unit\ volt$$

Or

$$1\ Farad\ will\ store\ one\ coulomb\ of\ charge\ when\ the\ difference\ across\ it\ is\ 1\ volt$$

Example

A capacitor stores 4×10^{-4} C of charge when the potential difference across it is 100 V. Calculate the capacitance.

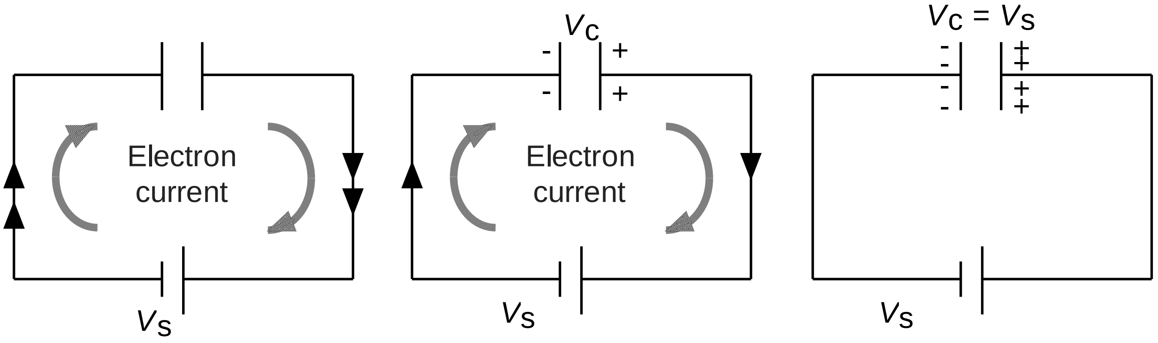
$Q = 4 \times 10^{-4}$ C
V = 100V
C = ?

$$C = \frac{Q}{V} = \frac{4 \times 10^{-4}}{100} = 4 \times 10^{-6}\ F = \underline{4\ \mu F}$$

Energy stored in a capacitor

A charged capacitor stores _electrical energy_.

Consider the charging of a parallel plate capacitor as shown below:



When the current is switched on, electrons flow onto one plate of the capacitor and *away* from the other plate.	This results in one plate becoming negatively charged and the other plate positively charged. A potential difference is set up across the plates.	Eventually the current ceases to flow. This happens when the pd across the plates of the capacitor is equal to the supply voltage.

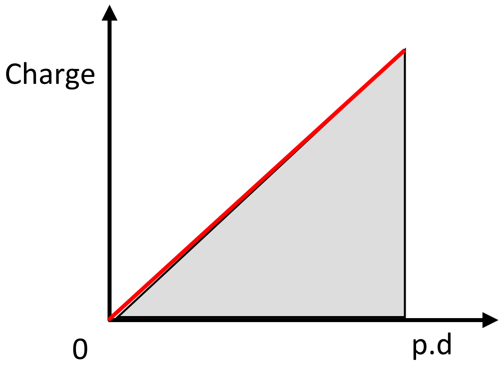
When charging a capacitor, the negatively charged plate will tend to _repel_ the electrons approaching (like charges repel). In order to overcome this repulsion, work has to be done in charging the capacitor. This is energy that is supplied by the battery.

Note that current does not flow through the capacitor, electrons flow *onto* one plate and *away from* the other plate.

The work done by the battery is stored as energy in the capacitor.

Q-V graphs

Consider a capacitor being charged to a potential difference, V and holding a charge Q. The following graph shows the capacitor being charged:



$$\text{Energy stored by capacitor} = \text{Area under graph}$$

$$\text{Area under graph} = \frac{1}{2}\ x\ Q\ x\ V$$

$$E = \frac{1}{2}QV$$

As we have previously stated, we know Q = CV. This allows us to make the following substitutions.

$$E = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{1}{2}\frac{Q^2}{C}$$

These equations only apply to capacitors and cannot be used for other components.

Example

A 40 µF capacitor is fully charged using a 50 V supply. Calculate the energy stored in the capacitor.

$C = 40 \times 10^{-6}$ F

V = 50 V

E = ?

Energy = ½CV^2

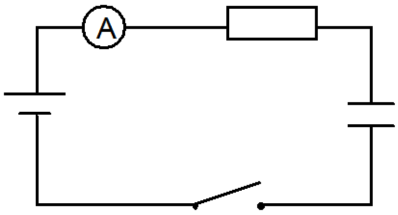
= ½ × 40 × 10^{-6} × 50^2

= <u>0.05 J</u>

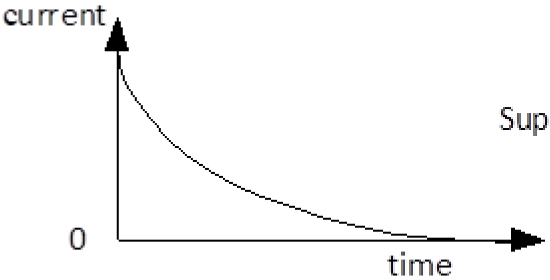
Charging and discharging a capacitor

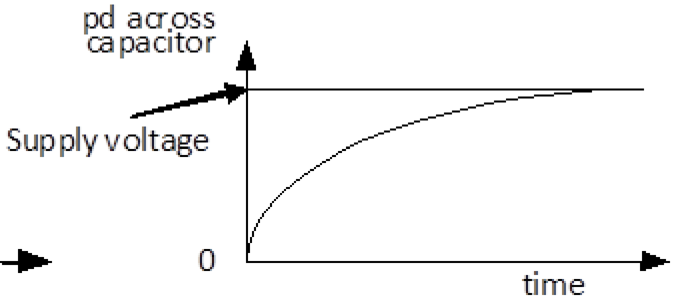
Charging

Consider the following circuit:

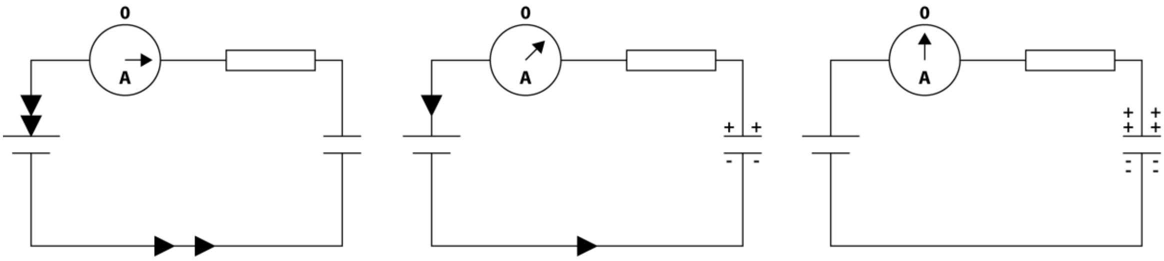


When the switch is closed the current flowing in the circuit and the voltage across the capacitor behave as shown in the graphs below:





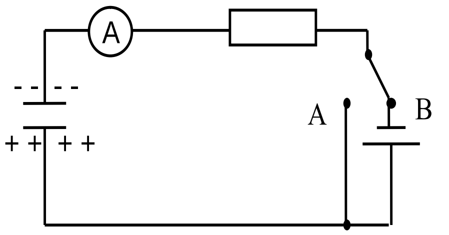
Consider the circuit at three different times.



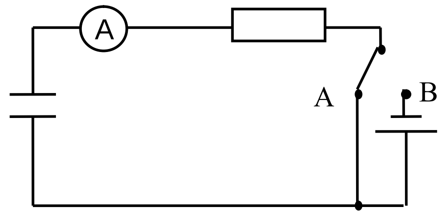
As soon as the switch is closed there is _no charge_ on the capacitor. The current is limited only by the resistance in the circuit and can be found using Ohm's law.	As the capacitor charges a pd develops across the plates which opposes the pd of the cell. As a result, the current from the supply _decreases_	The capacitor becomes fully charged and the pd across the plates is equal and opposite to that across the cell and the charging current becomes _zero_.

Discharging

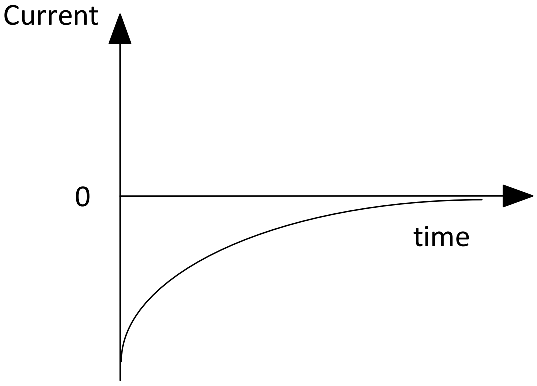
Consider the circuit opposite in which the switch is set to B and the capacitor is fully charged:

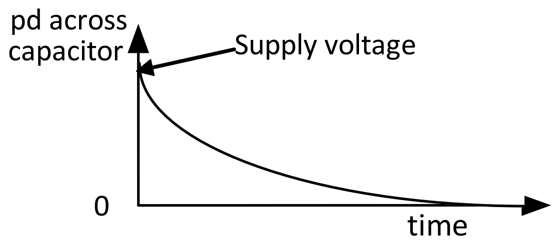


If the cell is shorted out of the circuit By setting the switch to A, the capacitor will discharge:



While the capacitor is discharging, the current in the circuit and the voltage across the capacitor behave as shown in the graphs below:





Although the current/time graph has the same shape as that during charging, the currents in each case are flowing in _opposite directions_. The discharging current decreases because the pd across the plates decreases as charge leaves them.

A capacitor stores charge, but unlike a cell it has no capability to supply more energy. When it discharges, the energy stored will be used in the circuit, eg in the above circuit it would be dissipated as heat in the resistor.

Factors affecting the rate of charge and discharge

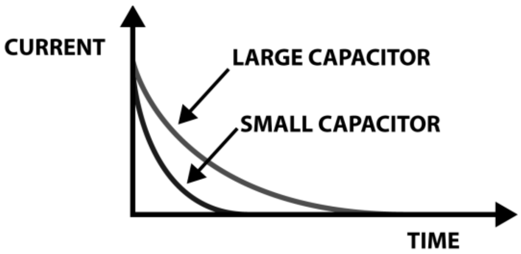
The time taken for a capacitor to charge is controlled by the resistance of the resistor *R* (because it controls the size of the current, ie the charge flow rate) and the capacitance of the capacitor (since a larger capacitor will take longer to fill and empty).

As an analogy, consider charging a capacitor is like filling a jug with water. The size of the jug is like the capacitance and the resistor is like the tap you use to control the rate of flow.

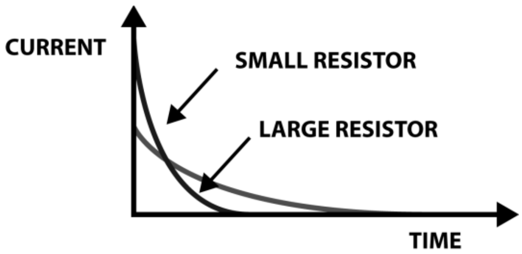
The values of *R* and *C* can be multiplied together to form what is known as the time constant. Can you prove that $R \times C$ has units of time, seconds? The time taken for the capacitor to charge or discharge is related to the time constant.

Large capacitance and large resistance both increase the charge or discharge time.

The *I*/*t* graphs for capacitors of different value during charging are shown below:



The effect of capacitance on charge current

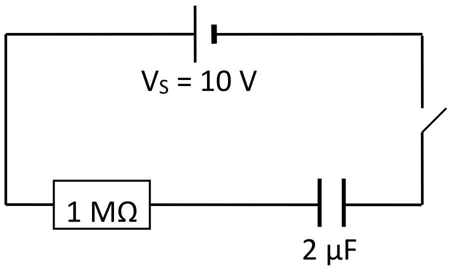


The effect of resistance on charge current

Note that since the area under the *I*/*t* graph is equal to charge, for a given capacitor the area under the graphs must be equal.

Worked example

The switch in the following circuit is closed at time t = 0.



(a) Immediately after closing the switch what is
  (i) the charge on the capacitor?
  (ii) the pd across the capacitor?
  (iii) the pd across the resistor?
  (iv) the current through the resistor?

(b) When the capacitor is fully charged what is
  (i) the pd across the capacitor?
  (ii) the charge stored on the capacitor?

a) (i) The initial charge on the capacitor is zero.

(ii) The initial pd across the capacitor is zero since there is no charge.

(iii) pd across the resistor is 10 V ($V_R = V_S - V_C = 10 - 0 = 10$ V)

(iv) $I = \frac{V}{R} = \frac{10}{10^6} = 1 \times 10^{-5}$ A

(b) (i) Final pd across the capacitor equals the supply voltage, 10 V.

(ii) $Q = VC = 2 \times 10^{-6} \times 10 = 2 \times 10^{-5}$ C

Semiconductors and p-n junctions

Conductors, Semiconductors and Insulators

Classifying materials

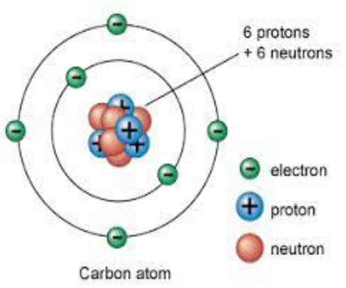
By considering the electrical properties of materials, we can divide them into three groups:

Material	Electrical properties
Conductor	Materials with many free electrons. These electrons can easily be made to flow through the material, hence conducting electricity. Examples: all metals, semi-metals like carbon- graphite, antimony and arsenic.
Insulator	Materials that have very few free electrons, and hence cannot conduct electricity. Examples: plastic, glass and wood.
Semiconductor	Materials that behave like insulators when pure, but will conduct when an impurity is added and/ or in response to light, heat, voltage etc. Examples: Elements: silicon, germanium, selenium Compounds: gallium arsenide and indium antimonide

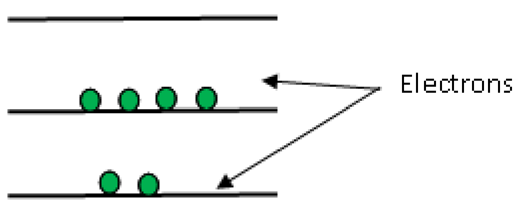
Band structure

An atom consists of a positively charged nucleus containing _protons_ and _neutrons_, and has _electrons_ orbiting the nucleus. In an isolated atom the electrons occupy _discrete energy levels_.

Discrete energy levels

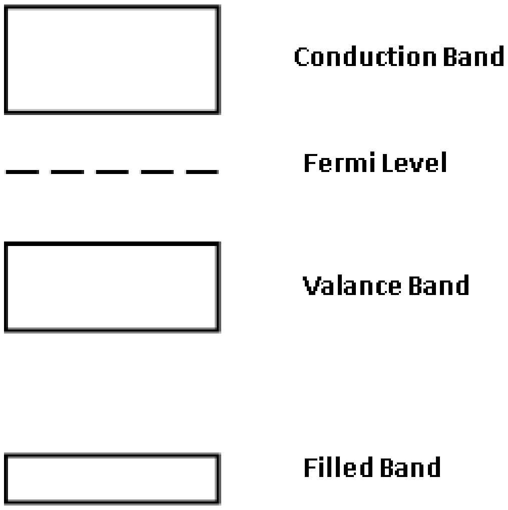


Energy level diagram for the isolated atom



Each energy level can hold a certain number of electrons. Electrons can only exist on each energy level – not in the gaps between them. Electrons will always fill the _lowest_ energy levels first.

When atoms are close to each other (such as in a solid lattice), they can share energy levels with their neighbours. However, they still cannot occupy the same energy levels, therefore many there are many energy levels of slightly difference energies for electrons to exist on. Therefore, in a solid lattice there are _energy bands_ for electrons to exist within, rather than the discrete energy levels seen by isolated atoms.

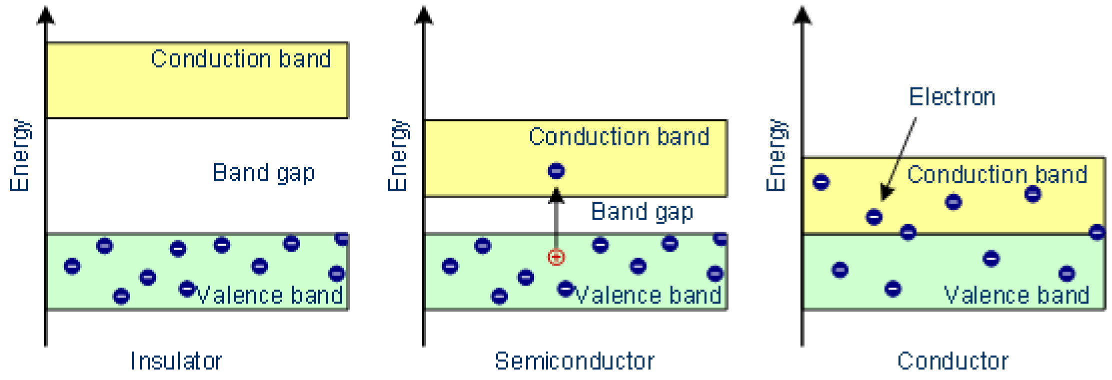


In between each energy band is a gap where electrons are not allowed. This is known as a _band gap_.

Similar to the energy levels of an individual atom, the electrons in a solid will fill the lower bands first. The Fermi level gives a rough idea of the energy level which electrons will generally fill up to, but there will always be some electrons with individual energies above this.

Electrical conduction in conductors, insulators and semiconductors

Band theory allows us to understand the electrical properties of conductors, insulators and semiconductors.

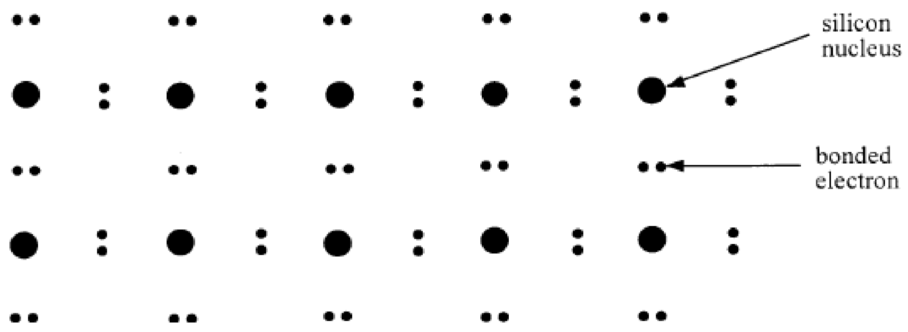


Material	Band Structure
Conductor	In a conductor the highest occupied energy band is only _partially filled_. This is known as the Conduction Band. There are many empty energy levels available close to the occupied levels for the electrons to move into. Therefore, electrons can flow easily from one atom to another when a potential difference is applied.
Insulator	In an insulator, the highest occupied band is completely _full_ of electrons. This is known as the valance band. There are no electrons in the band above this, i.e. the conduction band. There is a large gap between the bands called the *band gap*. The band gap is so large that electrons almost never cross it and the solid never conducts. If we supply enough energy the solid will conduct but often the large amount of energy needed ends up destroying the solid.
Semiconductor	Semiconductors are like insulators in that the highest occupied band is completely _full_, i.e. the valence band. However, the gap between the two bands is small and at room temperature some electrons have enough energy to jump the gap. At warm temperatures the solid will conduct to a small extent. As the temperature increases, the number of electrons in the conduction band _increases_ and so the semiconductor conducts better.

Bonding in Semiconductors

Intrinsic semiconductors

The most commonly used semiconductors are silicon and germanium. Both these materials have a *valency of four* (they have _four outer electrons_ available for bonding). In a pure crystal, each atom is bonded covalently to another four atoms. All of its outer electrons are bonded and therefore there are few free electrons available to conduct. These semiconductors have a very large resistance.

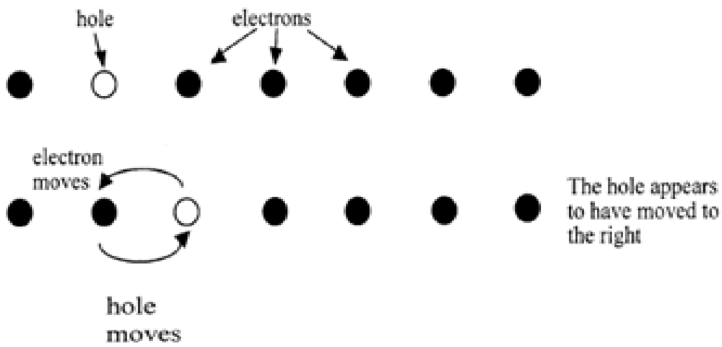


Imperfections in the crystal lattice and thermal ionisation due to heating can cause a few electrons to become free. A higher temperature will result in more free electrons, increasing conductivity and thus decreasing the resistance e.g. as in a thermistor.

Holes

When an electron leaves its position in the crystal lattice, there is a space left behind that is positively charged. This lack of an electron is called a _***positive hole***_.
This hole may be filled by an electron from a neighbouring atom, which will in turn leave a hole there. Although it is technically the electron that moves, the effect is the same as if it was the hole that moved through the crystal lattice. The hole can then be thought of as a positive charge carrier.

In an intrinsic (undoped) semiconductor, the number of holes is _equal_ to the number of electrons.



p – n junctions

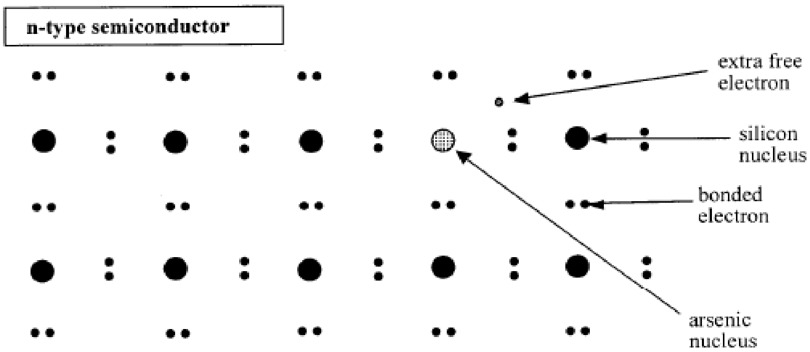
Doping

The electrical properties of semiconductors make them very important in electronic devices such as transistors, diodes and light dependant resistors (LDRs).

Doping is the addition of a very small amount of _impurity_ e.g. arsenic, to a pure semiconductor. This action dramatically changes the electrical properties of a material, i.e. allows a semiconductor to conduct. Once doped these materials are known as _***extrinsic semiconductors***_.

n –type semiconductors

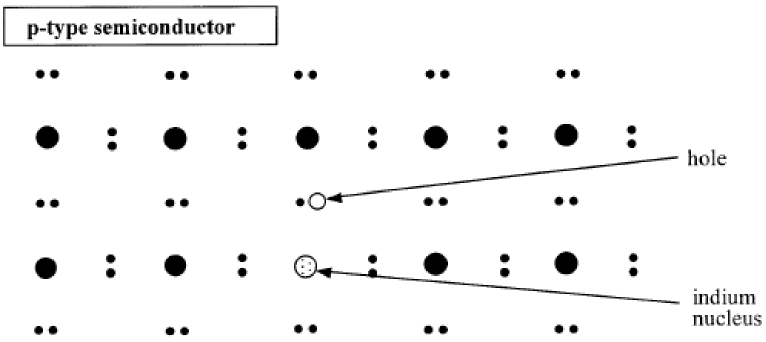
If an impurity such as arsenic (As), which has five outer electrons, is present in the crystal lattice, then four of its electrons will be used in bonding with the silicon. The fifth will be free to move about and conduct. Since the ability of the crystal to conduct is increased, the resistance of the semiconductor is therefore reduced.



This type of semiconductor is called _*n-type*_, since most conduction is by the movement of free electrons, which are _negatively charged_.

p –type semiconductors

A semiconductor may also be doped with an element like indium (In), which has only three outer electrons. This produces a hole in the crystal lattice, where an electron is 'missing'.

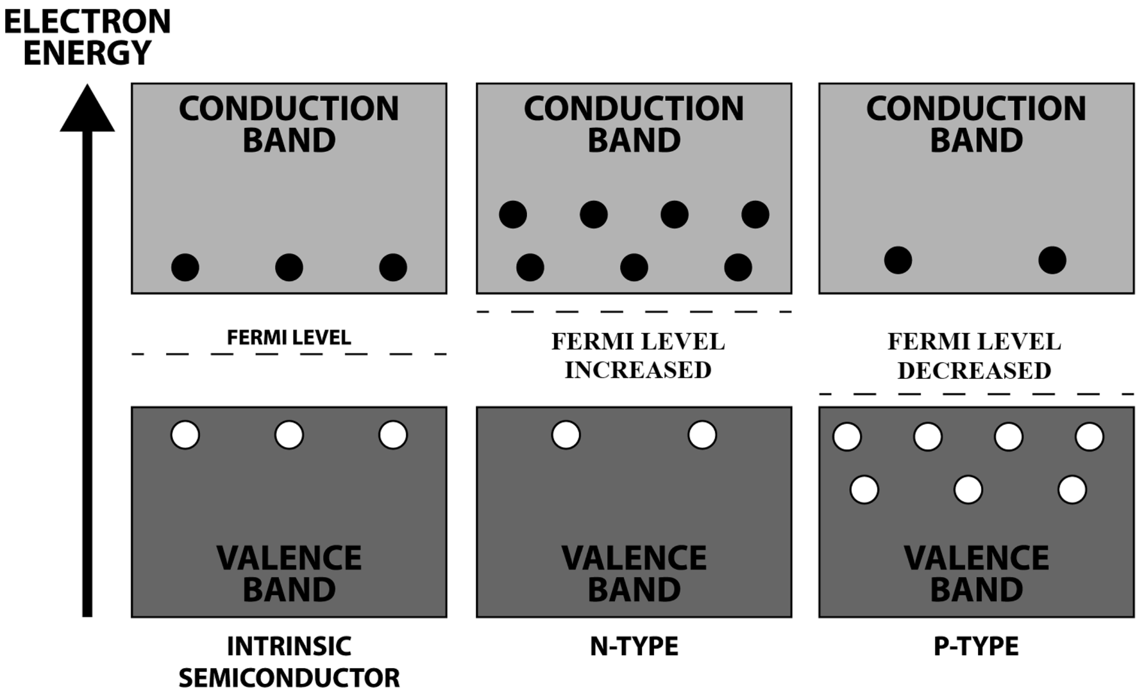


An electron from the next atom can move into the hole created as described previously. Conduction can thus take place by the movement of positive holes. This is called a _*p-type*_ semiconductor, as most conduction takes place by the movement of _positively charged 'holes'_.

How doping affects Band Structure

In terms of band structure, we can represent the electrons as dots in the conduction band, and holes as circles in the valance band, as shown in the diagram below.

The diagram also illustrates how the additional energy levels produced by the addition of the impure atoms changes the **Fermi level** and make it easier for electrons to move up to the conduction band in n-type semiconductors and for holes to be created in the valance band of the p-type.

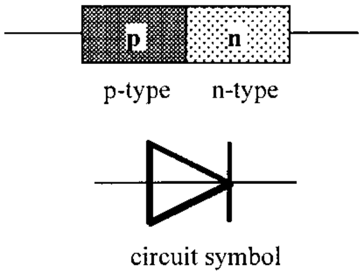


n –type semiconductor: _extra electrons present, the Fermi level is closer to the conduction band_.

p – type semiconductor: _fewer electrons present, the Fermi level is closer to the valence band_.

p – n junctions

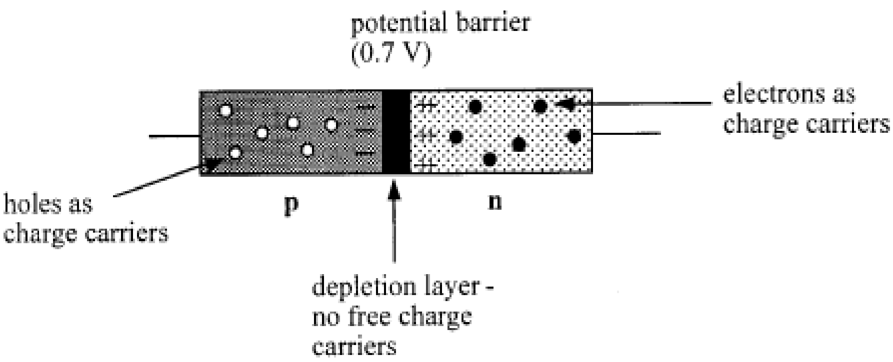
When a semiconductor is grown so that one half is _p-type_ and the other half is _n-type_, the product is called a p-n junction and it functions as a diode.



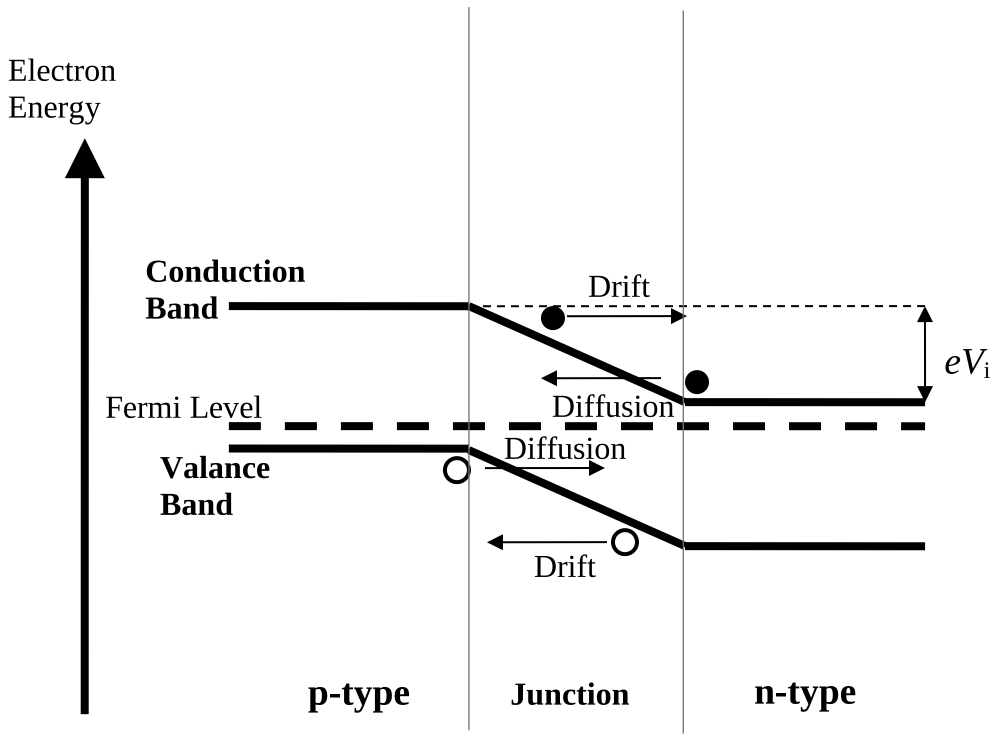
The excess electrons in the n-type material and the excess holes in the p-type material will constantly _diffuse_ (spread out). The charge carriers near the junction (join between p and n materials) will be able to diffuse across it.

Therefore, some of the free electrons from the _n-type_ material will diffuse across the junction and fill some of the holes in the _p-type_ material. This can also be thought of as holes moving in the opposite direction to be filled with electrons.

Since the n-type has lost electrons, it becomes positively charged near the junction. The p-type having gained electrons becomes negatively charged.
There will be a small voltage, a potential barrier, across the junction due to this charge separation. This voltage will tend to oppose any further movement of charge. The region around the junction has lost virtually all its free charge carriers. This region is called the _*depletion layer*_.



p– n junctions: Band energy diagrams



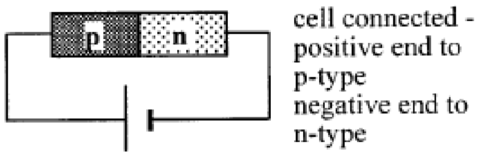
At the junction diffusion occurs of electrons from n-type to p-type material and of holes from p-type to n-type material. This results in a charge imbalance as an excess of negative charges now exist in the p-type material and a surplus of holes are present on the n-type material.

As like charges repel, this will tend to cause the drift of charge carriers back across the junction. Once this drift balances the diffusion in the opposite direction, equilibrium is reached and the Fermi level (where you are likely to find electrons) will be flat across the junction.

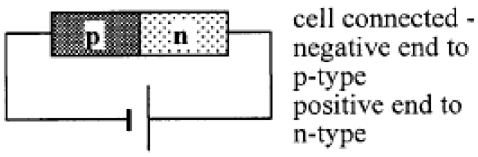
The lack of electrons in the n-type side lowers the conduction band and the lack of holes in the p-type side raises the valence band.

Biasing the diode

To bias the diode an external voltage is applied to it. They are two ways of connecting a cell to the diode to bias it; forward and reverse bias.

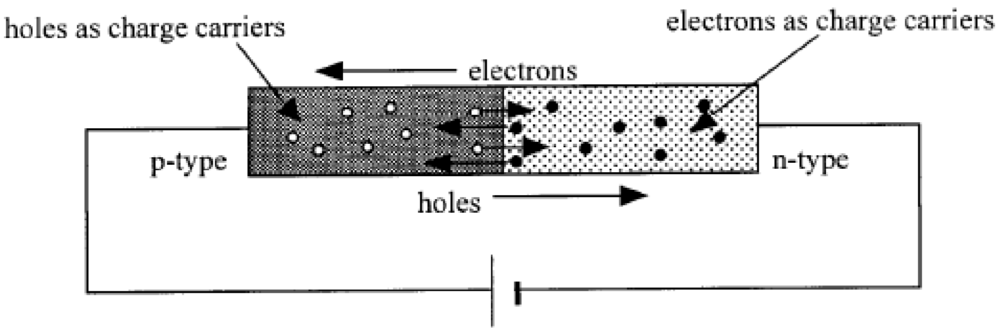


Forward-biased



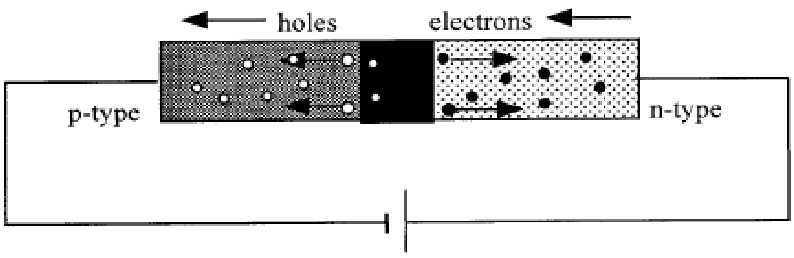
Reverse-biased

The forward – biased diode



When the cell is connected as above, the electrons from the n-type will be given enough energy from the battery to overcome the _depletion layer p.d_ (the potential barrier) and flow through the junction and round the circuit in an anti-clockwise direction. This movement will result in a similar movement of holes in the clockwise direction. **_The diode conducts because the depletion layer has been removed_.**

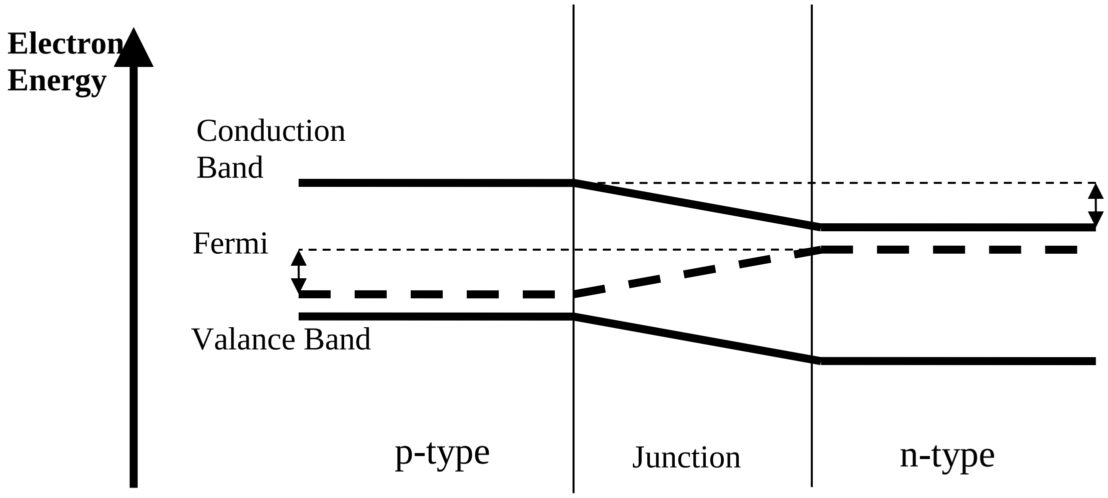
The reverse – biased diode



When the cell is connected as above, the applied potential causes the depletion layer to increase in width thus increasing the size of the potential barrier. **_Almost no conduction can take place_.**

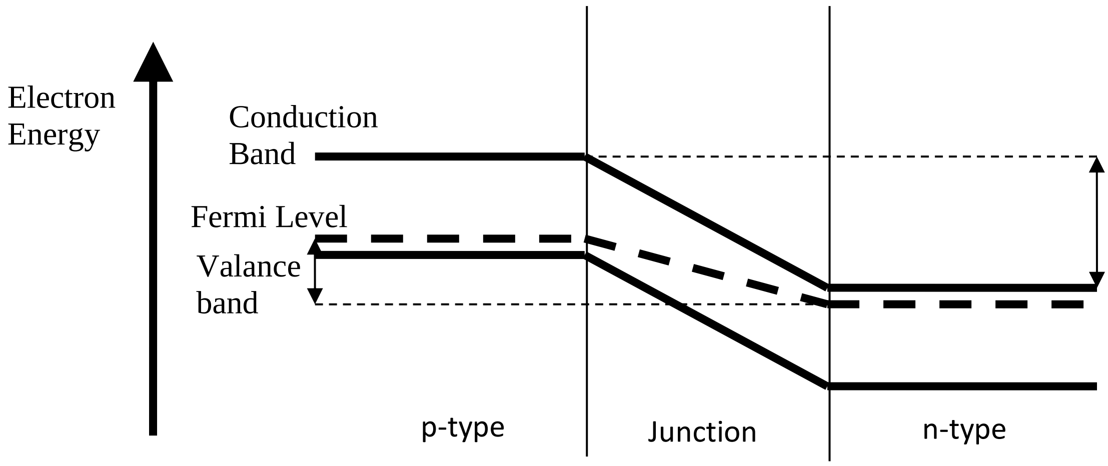
Forward – bias: Band energy diagram

Applying forward bias has the effect of lowering the bands on the p-side from where they were originally. As the applied voltage approaches the built in voltage, more electrons will have sufficient energy to flow up the now smaller barrier and an appreciable current will be detected. Once the applied voltage reaches the in-built voltage there is no potential barrier and the p–n junction presents almost no resistance, like a conductor. The holes are similarly able to flow in the opposite direction across the junction towards the negative side of the battery.



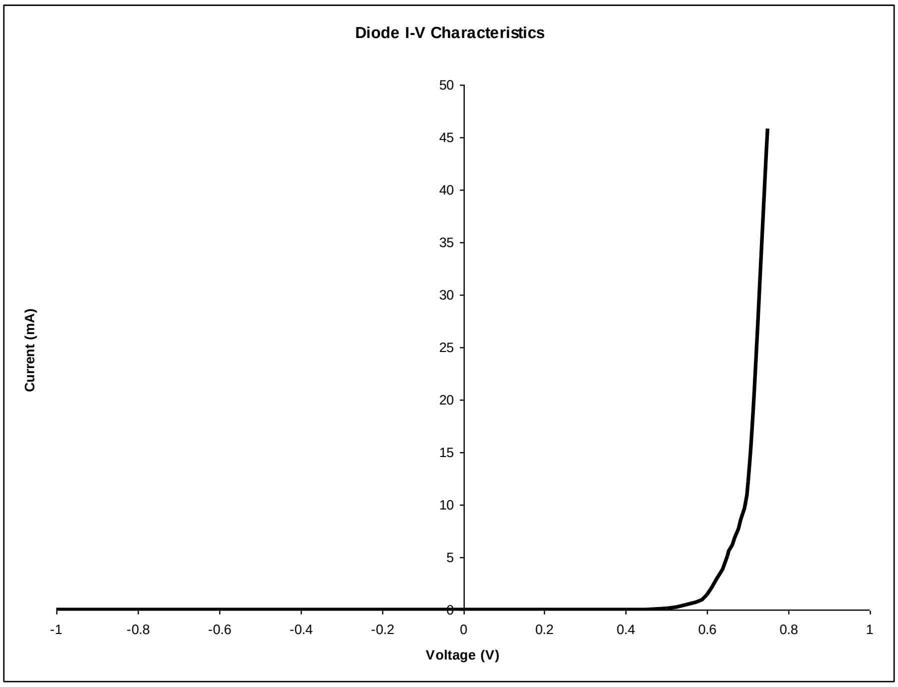
Reverse – bias: Band energy diagram

Applying a reverse bias has the effect of raising the bands on the p-side from where they were originally. Almost no conduction can take place since the battery is trying to make electrons flow 'up the slope' of the difference in the conduction bands. The holes face a similar problem in flowing in the opposite direction. The tiny current that does flow is termed reverse **leakage current** and comes from the few electrons which have enough energy from thermal ionisation to make it up the barrier.



Electrical characteristics

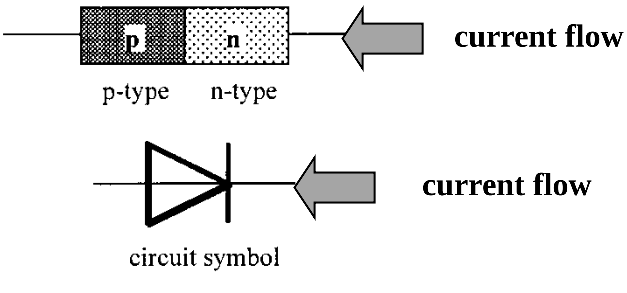
A graph of the variation of current with pd across a p–n junction is shown below:



When the applied voltage reaches the in-built voltage there is no potential barrier, therefore the p–n junction presents almost no resistance and a large current flows.

Current flow in p-n junctions

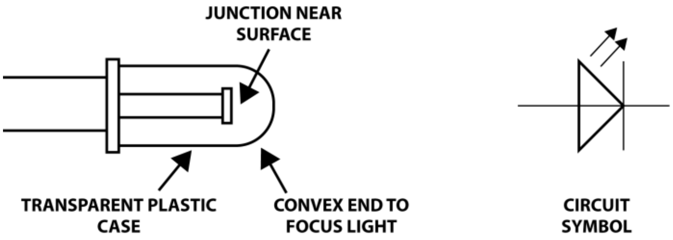
In conclusion, a p-n junction will only allow current to flow through it _one way_, as indicated below.



In practice, a very small current will flow in the opposite direction i.e. the leakage current. This is important in some applications such as a light dependant resistor.

The light emitting diode (LED)

One application of the p-n junction is the LED. An LED consists of a _p-n junction diode_ connected to a positive and negative terminal. The junction is encased in a transparent plastic as shown below.



How does an LED work?

When the p-n junction is connected in forward bias, electrons and holes will pass through the junction in opposite directions. Some of the electrons and holes will meet and _recombine_. When this happens energy is emitted in the form of a photon of light.

$$Electron + Hole = Photon\ of\ light$$

The size of the bandgap between conduction and valence bands indicates the _frequency_ of the photon emitted. The larger the gap, the _higher_ the frequency of light emitted by the LED.

The recombination energy can be calculated using the equation:

$$E = hf$$

Where E is the _energy of the photon_,
h is _Planck's constant (6.63×10^{-34}Js)_,
and f is _the frequency of the emitted light_.

LED: worked example

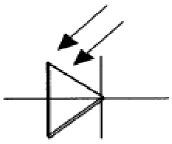
An LED emits photons of light with a frequency of 5×10^{14} Hz.
Calculate:

(a) The wavelength of the photons of light.
(b) What colour of light is emitted by this LED?
(c) What factor about the construction of the LED determines the colour of the emitted light?

(a) $v = f \times \lambda$
$3 \times 10^8 = 5 \times 10^{14} \times \lambda$
λ = 600 nm
(b) Orange (selected from the data sheet)
(c) The type of materials used to construct the semiconductor.

The Photodiode

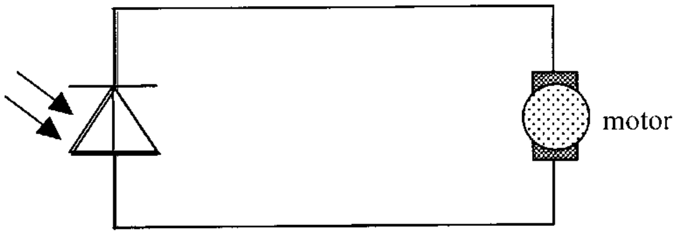
A p-n junction in a transparent coating will react to light due to the _photoelectric effect_.



The photodiode can be used in two modes; _photovoltaic mode_ and _photoconductive mode_.

Photovoltaic Mode (No Power Supply)

In this mode the diode has no bias applied as shown in the diagram below. The load may be a component other than a motor.

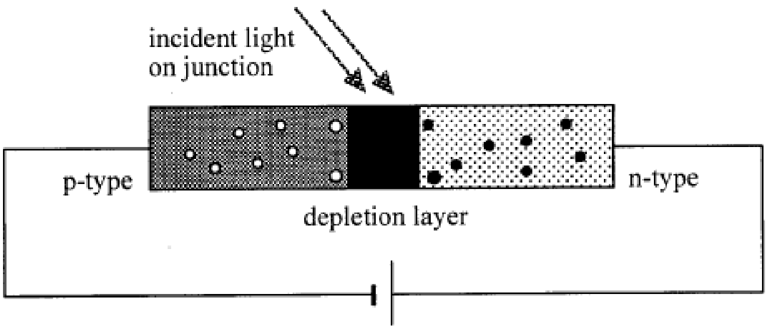


Photons that are incident on the junction have their _energy_ absorbed, freeing electrons and creating _electron-hole pairs_. A voltage is generated by the separation of the electron and hole.

Using more _intense light_ (more photons incident per second) will lead to more electron-hole pairs being produced and therefore a higher voltage will be generated by the diode. In this mode, the photodiode will supply a voltage to the load, e.g. motor. Many photodiodes connected together form the basis of solar cells.

Photoconductive Mode

In this mode, a photodiode is connected to a supply voltage in _reverse bias_. As shown earlier, in this mode we would not expect the diode to conduct. This is true when it is kept in the dark.



However, when _photons of light_ shine on the junction electrons are freed and create _electron-hole pairs_ as describe for *photovoltaic mode*. This in turn creates a number of free charge carriers in the depletion layer, decreasing the resistance and enabling current to flow.

A _greater intensity of light_ will lead to more free charge carriers and therefore *less resistance.* The photodiode connected to a supply voltage, in reverse bias, acts as a _light dependant resistor (LDR)_.