St Ninian's HS

Higher Physics

Electricity

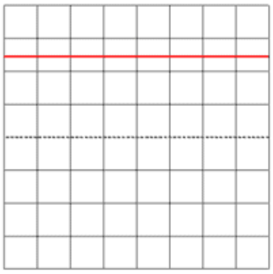
Pupil Notes

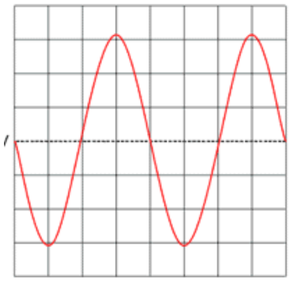
Monitoring & Measuring A.C.

A.C & D.C.

There are two types of electric current - **direct current** (d.c.) and **alternating current** (a.c)

A d.c. supply causes electrons to drift though the conductors of the circuit, always travelling in the same direction. Direct current is a constant value. This is apparent from the oscilloscope trace of a d.c. supply shown opposite.

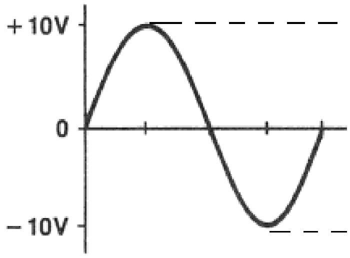




In an a.c. supply, however the electrons in the circuit flow firstly in one direction and then flow in the opposite direction as the polarity reverses regularly. Alternating current changes direction and value with time. This can also be seen on an oscilloscope trace.

Peak and Root Mean Square

The peak value of an a.c. supply is the maximum value reached by the current (or voltage). For example, the supply shown below has a peak value of 10 V.



When a bulb is connected to a 10 V d.c. supply and then to an a.c. supply with a peak voltage of 10 V, it is found that the bulb is brighter when the d.c. supply is used. The reason for this is that the d.c. supply remains at 10 V at all times, but the a.c. supply only reaches 10 V momentarily twice in each cycle and is less than 10 V at all other times. The average power of the a.c. supply is therefore less than the power of the d.c. source.

Clearly, then, for an a.c. source to produce the same power as a 10 V d.c. supply, it must have a peak voltage greater than 10 V. An a.c. supply whose peak voltage is V_{peak}, produces the same power as a d.c. supply whose voltage is 0.7 x V_{peak}. The equivalent d.c. supply is known as the root mean square (r.m.s.) value of an a.c. source.

So : $V_{rms} = 0.7 \times V_{peak}$

Or to be more accurate: $\boxed{V_{peak} = \sqrt{2} \times V_{rms}}$

It is always the r.m.s. value of an a.c. supply which is quoted. For example the mains voltage is 230 V.

Example 1

What is the peak value of the mains supply?

$$\begin{aligned} V_{peak} &= \sqrt{2} \times V_{rms} \\ &= \sqrt{2} \times 230 \\ &= 325\ V \end{aligned}$$

Example 2

What is the r.m.s. value of a supply with a peak voltage of 50 V?

$$\begin{aligned} V_{rms} &= \frac{V_{peak}}{\sqrt{2}} \\ &= \frac{50}{\sqrt{2}} \\ &= 35\ V \end{aligned}$$

The relationship between the r.m.s. current and the peak current is exactly the same.

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

Frequency of A.C. Supply

To describe the domestic supply voltage fully, we would have to include the frequency i.e. 230 V, 50 Hz. The frequency of an a.c. supply is the number of complete cycles in one second and can be measured using a calibrated oscilloscope.

To measure the frequency you need to look at both the trace on the oscilloscope screen and the controls of the oscilloscope.

- First, find the wavelength of the trace on the screen.
- Secondly, read the value of the time base setting.
- Calculate the period (T) of the wave by finding the product of the wavelength and the time base setting.
- Finally, calculate the frequency (f) using the relationship : $\boxed{f = \frac{1}{T}}$

Example 1

If the period of the supply is 25 ms, find the frequency.

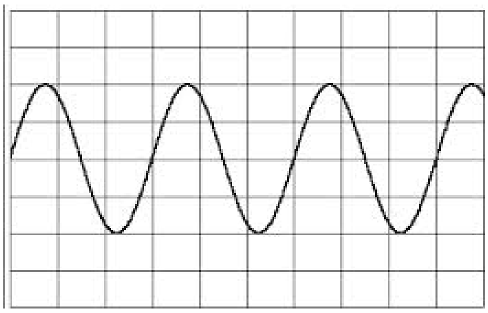
$$f = \frac{1}{T}$$

$$= \frac{1}{25 \times 10^{-3}}$$

$$= 40 \text{ Hz}$$

Example 2

The oscilloscope trace below shows the voltage from an a.c. supply.



(a) *If the oscilloscope voltage control is set at 5 V per division, calculate the peak voltage.*

$$V_{peak} = 5 \times 2 = 10 \text{ V}$$

(b) *What is the r.m.s. voltage?*

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

$$= \frac{10}{\sqrt{2}}$$

$$= 7.1 \text{ V}$$

(c) *If the time base seting is 10 ms/cm, calculate the frequency of the a.c supply.*

$T = \lambda$ x time base setting
$= 3 \times 10$
$= 30$ ms

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

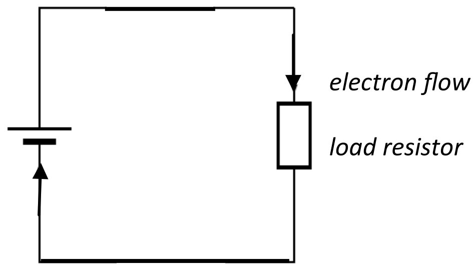
$$= \frac{1}{30 \times 10^{-3}}$$

$$= 33 \text{ Hz}$$

Circuits

Electromotive Force (e.m.f.)

When a conductor is placed in an electric field, the charged particles in the atoms of the conductor experience an electric force. Those electrons which are not bound to atoms can respond to this force by moving through the conductor. This flow of electrons is an electric current. The supply in a circuit provides an electric field which cause charges to move.



A simple 1.5 V cell provides electrons with energy as they pass through. The energy that is given to each coulomb of charge as it passes through a supply is known as the electromotive force (e.m.f.).

The e.m.f. (E) can be calculated by using the following formula :

$$\boxed{E = \frac{W}{Q}}$$

where W is the energy in joules and Q is the charge in coulombs. The e.m.f. E is therefore measured in volts.

The difference between sources such as cells, batteries, dynamos etc., is in the amount of energy they give to the charges flowing in the circuit. A 1.5 V cell gives each coulomb of charge 1.5 J of energy; a 12 v battery gives each coulomb of 12 J energy ; and so on.

Notice the difference between **e.m.f.** (E) and the **potential difference** (V) across the components in the circuit. The e.m.f. E measures the electrical energy given to the charge : the p.d. V measures the electrical energy lost by the charge. The lost energy is transformed to heat, light etc in the components.

Electric Current

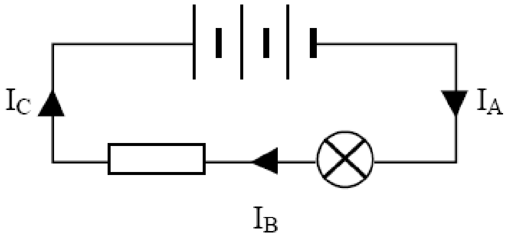
Electric current is a measure of the flow of charge around a circuit and depends on the amount of charge passing any point in a circuit every second.

$$\boxed{Q = It}$$

Electric current (I) is measured in amperes, A. Electric charge (Q) is measured in coulombs, C. Time (t) is measured in seconds, s.

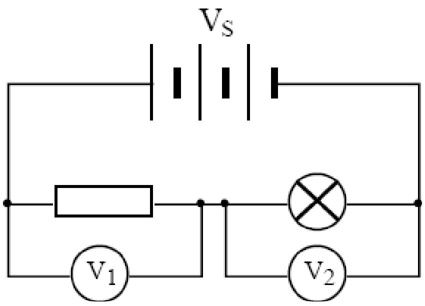
Current and Potential Difference in Series Circuits

The current is the same at all points in a series circuit. One way to remember this is that there is **only one** path for the current to flow.



$$I_A = I_B = I_C$$

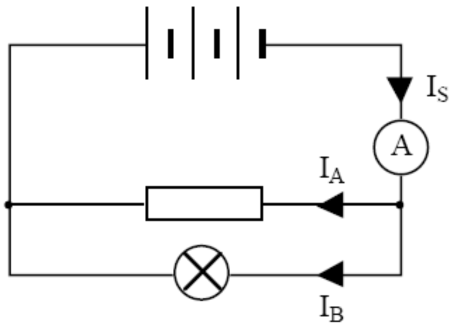
The sum of the potential difference across the components in a series circuit is equal to the voltage of the supply.



$$V_S = V_1 + V_2$$

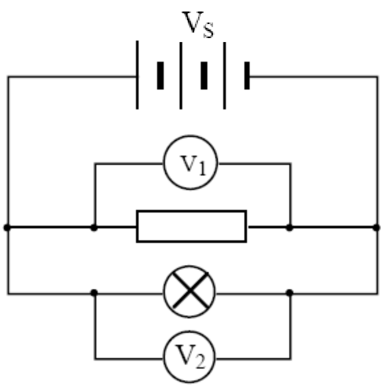
Current and Potential Difference in Parallel Circuits

In a parallel circuit the current has **more than one** path to follow. This means that the supply current splits through each parallel branch.



$$I_S = I_A + I_B$$

The potential difference across components is the same for all components.



$$V_S = V_1 = V_2$$

Electrical Resistance

Resistance is a measure of the opposition of a circuit component to the current through that component. The greater the resistance of a component, the smaller the current through that component. All normal circuit components have resistance and the resistance of a component is measured using the relationship:

$$\boxed{V = IR}$$

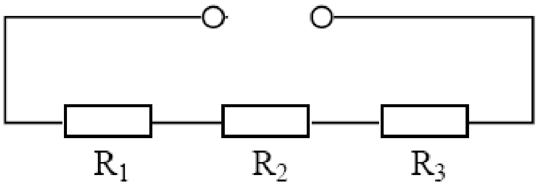
This relationship is known as **Ohm's Law,** named after a German physicist, Georg Ohm. For components called resistors, the resistance remains approximately constant for different values of current. **This means that the V/I = constant (R).**

Resistance in Circuits

Series Circuits

When more than one component is connected in series (like the circuit below), the **total resistance** of all the components is equivalent to one single resistor, R_T, calculated using the relationship:

$$\boxed{R_T = R_1 + R_2 + R_3}$$

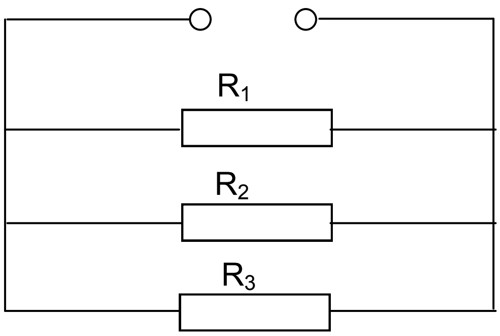


This relationship is true for two or more components connected in series.

Parallel Circuits

When more than one component is connected in parallel, the **total resistance** of all the components is equivalent to one single resistor, R_T, calculated using the relationship:

$$\boxed{\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$



This relationship is true for two or more components connected in parallel.

Power

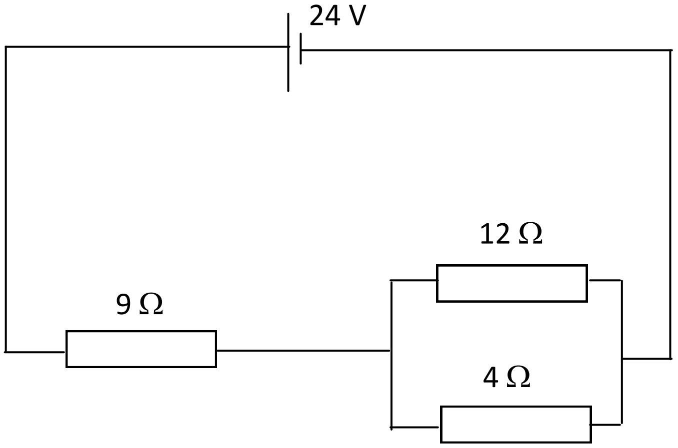
Power is the rate at which energy is converted from one form into another.
The power rating of an electrical component is the rate at which it transforms electrical energy.

$$P = \frac{E}{t}$$

The following formulae are also used to calculate power:

$$P = IV \qquad P = I^2R \qquad P = \frac{V^2}{R}$$

Example



(a) *What is the total resistance in the circuit?*

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\frac{1}{R_p} = \frac{1}{12} + \frac{1}{4}$$

$$\frac{1}{R_p} = \frac{1}{12} + \frac{3}{12}$$

$$\frac{1}{R_p} = \frac{4}{12}$$

$R_p = 3\Omega$ $\qquad$ $R_T = 3\Omega + 9\Omega = 12\Omega$

(b) *What is the current flowing from the supply?*

$$I = \frac{V_S}{R_T}$$

$$= \frac{24}{12}$$

$$= 2A$$

(c) *What is the current flowing in each of the resistors?*

Current through the 9 Ω resistor is 2 A (the supply current).

$$V = IR$$

$$= 2 \times 9$$

$$= 18V$$

Voltage across parallel branch = 24—18 = 6V

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

$$= \frac{6}{4} \qquad\qquad = \frac{6}{12}$$

$$= 1.5\ A \qquad\qquad = 0.5\ A$$

Current through the 4Ω is 1.5A and the current through the 12Ω is 0.5A.

(d) *Find the power dissipated in the 9 Ω resistor.*

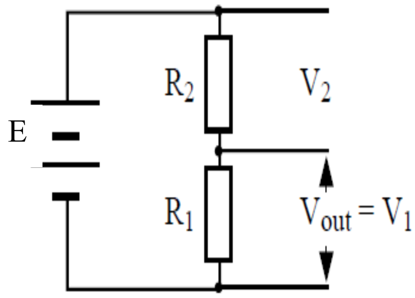
$$P = I^2R$$

$$= 2^2 \times 9$$

$$= 36W$$

Potential Divider Circuits

A potential divider is a device or a circuit that uses two (or more) resistors to provide a fraction of the available e.m.f. from the supply.



The p.d. from the supply is divided across the resistors in direct proportion to their individual resistances. The potential divider is a **series** circuit, therefore the current is the same at all points.

$I_{supply} = I_1 = I_2$ where I_1 = current through R_1 and I_2 = current through R_2

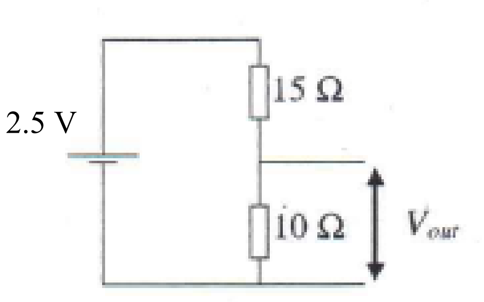
Using Ohm's Law:

$$\boxed{I = \frac{V}{R}} \qquad \text{Hence} \qquad \boxed{\frac{E}{R_T} = \frac{V_1}{R_1} = \frac{V_2}{R_2}}$$

$$\boxed{V_1 = \frac{R_1}{R_T} \times E} \quad \text{or} \quad \boxed{V_1 = \frac{R_1}{R_1 + R_2} \times E} \quad \text{and} \quad \boxed{\frac{V_1}{R_1} = \frac{V_2}{R_2}}$$

Example

Calculate the output p.d., V_{out}, from the potential divider circuit shown.



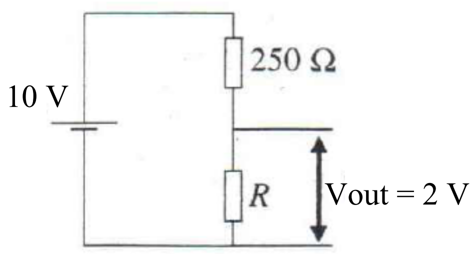
$$V_{out} = \frac{R_1}{R_T} \times E$$

$$= \frac{10}{25} \times 2.5$$

$$= 1\ V$$

Example

Calculate the value of R in the potential divider circuit shown below.



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

$$\frac{2}{8} = \frac{R}{250}$$

$$8R = 500$$

$$R = 62.5\ \Omega$$

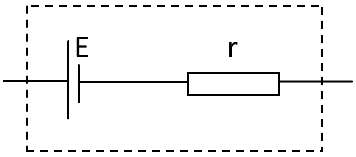
Internal Resistance

In choosing a suitable power supply for a circuit, you have to ensure that it:

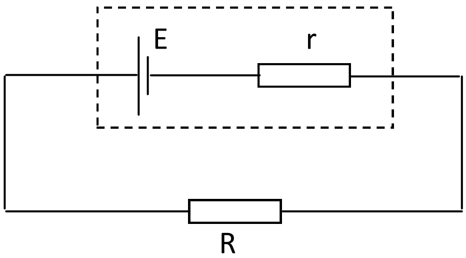
- gives the correct e.m.f. (see page 5 of the notes)
- is able to supply the required maximum current.

When a power supply is part of a circuit, it must itself be a conductor. All conductors, as you know, have some resistance. A power supply has ***internal resistance (r)***. This is due to the fact that work must be done to drive the charge through the supply itself. All power supplies have some internal resistance.

From now on we must consider all supplies to have both e.m.f. (E) and internal resistance (r) :



When a load resistor is connected to a supply, the current flowing is determined by the e.m.f. of the cell and the total resistance of the circuit. The total resistance is the sum of the internal and external resistances.



Using the conservation of energy round a circuit :

$$\boxed{E = Ir + IR}$$

The term IR is the potential difference (p.d.) across the load resistor R and is the ***terminal p.d.***, i.e. the p.d. which is available at the terminals of the supply. It is given the symbol V.

$$\boxed{\mathbf{E = Ir + V}}$$

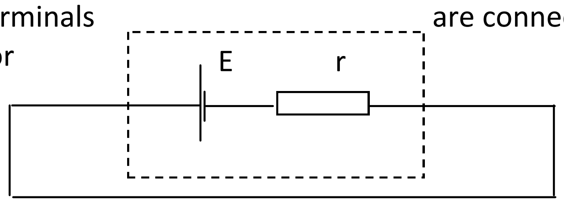
$$V = E - Ir$$

This equation shows that, if I = 0, then V = E, i.e. the terminal p.d. of the supply is equal to the e.m.f. only when the supply is delivering no current (an open circuit).

The term Ir is the p.d. across the internal resistance is often called the “lost volts”, because it is the difference between the voltage marked on the supply (E) and the voltage which actually appears at the terminals (V):

$$Ir = E - V$$

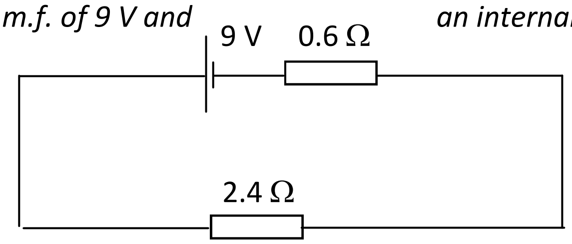
The presence of the internal resistance means that there is a maximum current which a supply is capable of delivering. The greatest current flows when the supply is short circuited, i.e. the terminals are connected directly to one another with no load resistor



The short circuit current is given by : $\boxed{\mathbf{I = \frac{E}{r}}}$

Example

A battery has an e.m.f. of 9 V and an internal resistance of 0.6 Ω.



(a) *What is the current when the battery is connected to a 2.4 Ω resistor?*

$R_T = 0.6 + 2.4 = 3.0\ \Omega$

Example continued.

$$I = \frac{E}{R_T}$$

$$= \frac{9}{3}$$

$$= 3\ A$$

(b) *What is the terminal potential difference?*

$$V = IR$$

$$= 3 \times 2.4$$

$$= 7.2\ V$$

(c) *What is the short circuit current of this battery?*

$$I = \frac{E}{r}$$

$$= \frac{9}{0.6}$$

$$= 15\ A$$

(d) *Calculate the lost volts if the load resistance in the circuit is increased to 3.9 Ω.*

$$R_T = 0.6 + 3.9 = 4.5\ \Omega$$

$$I = \frac{E}{R_T}$$

$$= \frac{9}{4.5}$$

$$= 2\ A$$

Lost volts = Ir = 2 x 0.6 = 1.2 V

Graph of E against I

As you know, the terminal potential difference of a supply decreases as the current drawn from it increases. A graph of this can be drawn. The graph is a straight line.

The equation

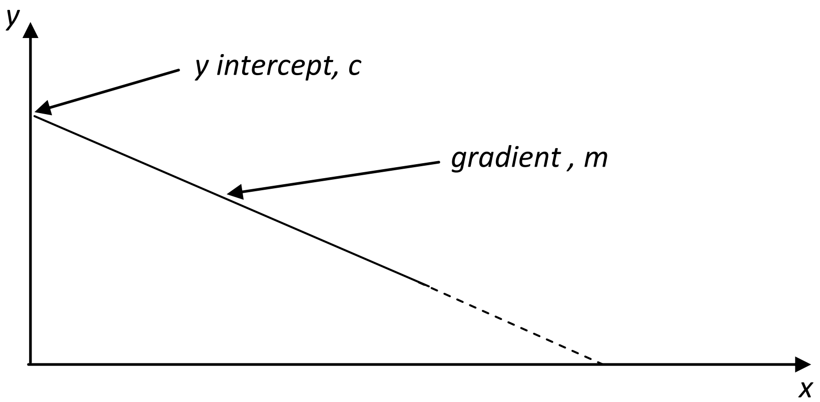
$$V = E - Ir$$

can be rearranged to give

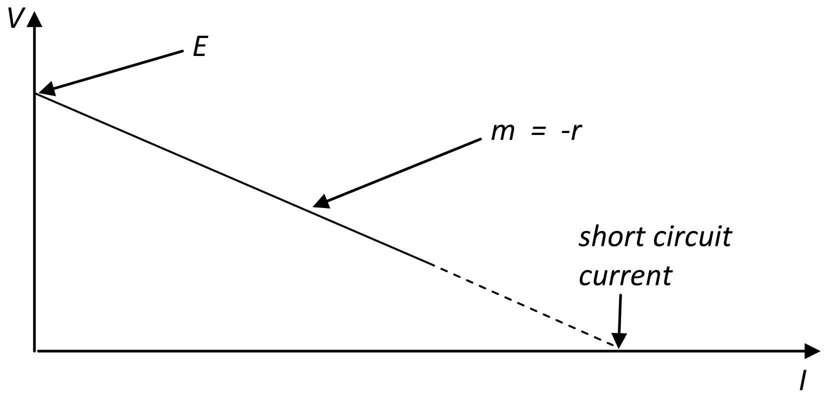
$$V = (-r)I + E$$

This has the same form as the equation of any straight line :

$$y = mx + c$$



On the vertical axis *y* and *V* correspond; on the horizontal axis *x* and *I* correspond. The intercept on the y-axis (c) therefore gives the value of *E* and the gradient of the line (*m*) gives the value of the internal resistance r, ignoring the negative sign.

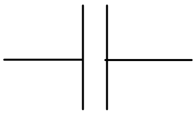


Extending the graph until it meets the horizontal axis gives the value of the short circuit current.

It is therefore possible to find E, r and the short circuit current from a set of experimental results by plotting a graph of *V* against *I*.

Capacitance

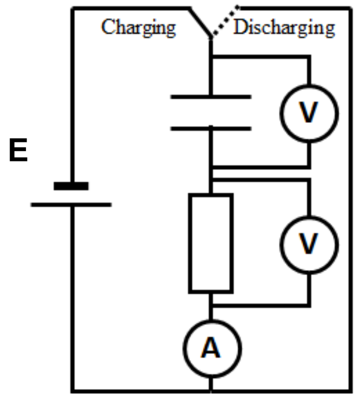
A capacitor is a device which can store charge. The ability to store charge is called capacitance. Capacitors consist of two conducting plates separated by an insulating layer. This gives rise to the circuit symbol for a capacitor:



Capacitance is represented by the symbol C and is measured in farads (F).

Charging and Discharging a Capacitor

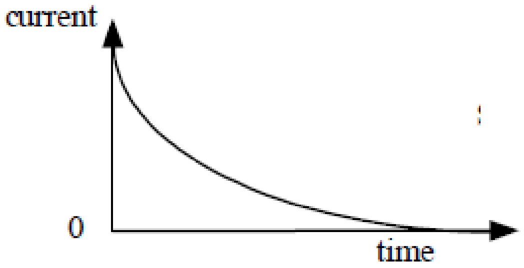
When a capacitor is connected directly to a power supply, the charging process is almost instantaneous. However, when a resistor is connected in series with the capacitor, charging takes longer. This can be investigated using the circuit below.

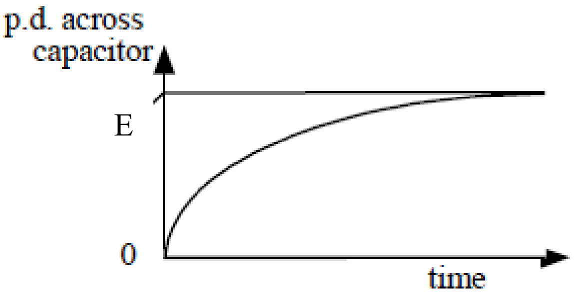


In the circuit the two way switch is moved position to allow both charging and discharging. During both charging and discharging, current flows through the resistor.

If the charging process is slow enough, it is possible to monitor the change in potential difference across the capacitor (V_c) using a voltmeter connected across the capacitor. The variation of current can be followed using an ammeter connected in series with the resistor. Otherwise an interface connected to a computer can be used.

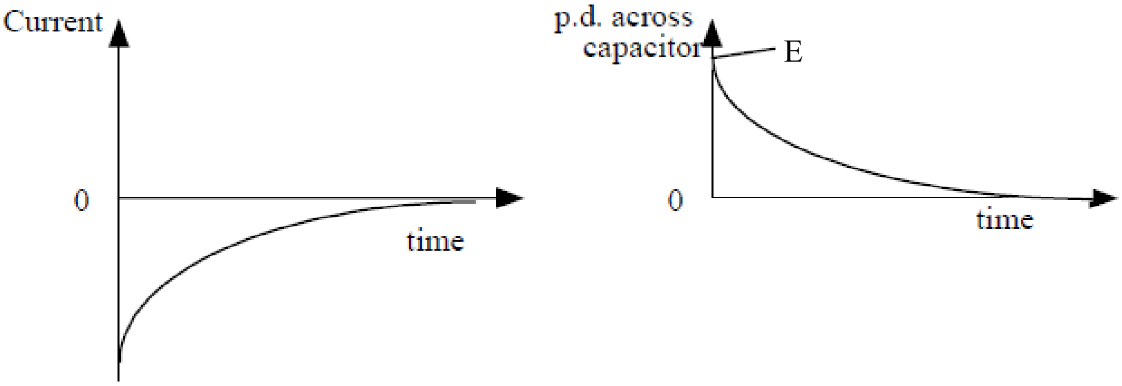
Charging The graphs of I and V_c against t obtained during charging are shown below.





As soon as the switch is closed the current rises up to a maximum before dying away to zero. We say that the current decays. Meanwhile, the voltage across the capacitor, which starts at zero rises, quickly at first, then moves slowly, finally levelling off at a value which is equal to the e.m.f. of the supply.

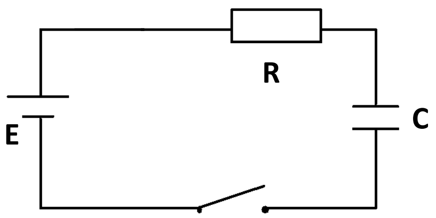
Discharging The graphs for the discharging process are shown below.



Again the current rises instantaneously to its maximum, **but this time flowing in the opposite direction**, before decaying to zero. The voltage drops quickly at first, then more slowly, reaching zero at the same time as the current ceases.

Current during Charging and Discharging

It is possible to find the value of the current which flows in the charging circuit when the switch is first closed:

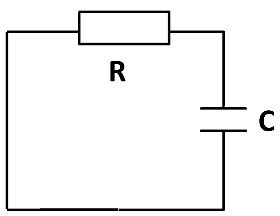


Initially the p.d. across the capacitor is zero and so there is no voltage opposing the e.m.f. of the cell. The current is therefore found by applying Ohm's Law:

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

As soon as the current begins to flow the capacitor begins to charge and there is an opposing p.d. across the capacitor. The current must therefore decrease. Finally, when the p.d. across the capacitor reaches the value of the supply e.m.f., no current will flow. The situation is similar to what happens when two cells are connected in series, but facing in opposite directions.

The initial current during discharging is exactly the same as during charging:



The p.d. across C when the switch is first closed is equal to the e.m.f. of the supply E.

Again the initial current is given by Ohm's Law.

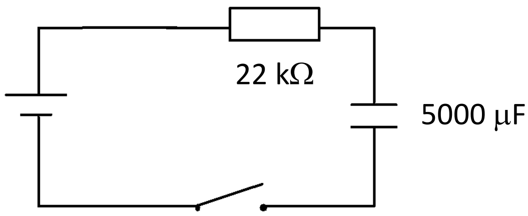
$$I = \frac{E}{R}$$

As soon as the current starts to flow the p.d. across the capacitor drops and so the current decreases.

The magnitude of the initial current is the same for both charging and discharging and depends only on the e.m.f. of the supply and the resistance, **not on the value of the capacitor.** When the capacitor is partially charged (or discharged) it is useful to consider the p.d. across the resistor, V_R, (the difference between E and V_c) and the resistance, R, when calculating the current.

Example

A 12 V battery is connected to a 5000 μF capacitor and a 22 kΩ resistor in series. What is the initial current when the connection is made?



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

$$= \frac{12}{22\,000}$$

$$= 5.5 \times 10^{-4}\ A$$

$$= 0.55\ mA$$

Example

When the charging process, in the circuit above, is partially complete the p.d. across the capacitor is found to be 9.0 V. What is the current now?

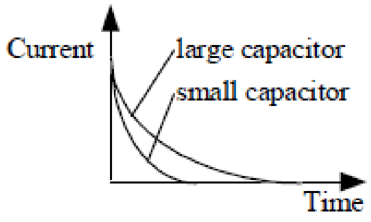
$$I = \frac{V_R}{R}$$

$$= \frac{3}{22\,000}$$

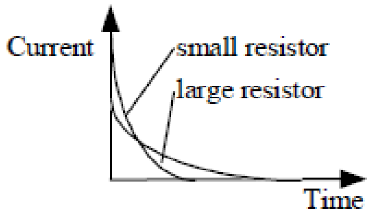
$$= 1.4 \times 10^{-4}\ A$$

Rate of Charge of a Capacitor

When a capacitor is charged to a given voltage the time taken depends on the value of the capacitor. The larger the capacitor the longer the charging time, since a larger capacitor requires more charge to raise it to the same p.d. as a smaller capacitor.



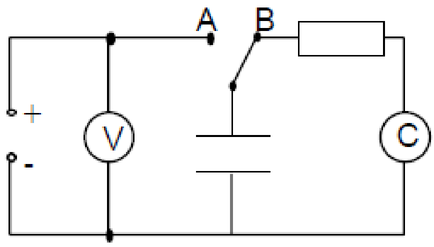
When a capacitor is charged to a given voltage the time taken depends on the value of the resistance in the circuit. The larger the resistance the smaller the initial charging current, hence the longer it takes to charge the capacitor as Q = It.



Relationship between Charge and Potential Difference

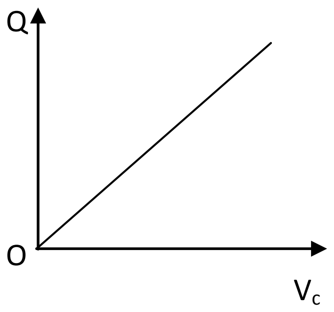
The potential difference across a capacitor depends on the charge upon it.

The circuit below can be used to investigate the relationship between the charge and the potential difference.



The capacitor is charged to a chosen voltage by setting the switch to A. The charge stored can be measured directly by discharging the capacitor through the coulombmeter when the switch is set to B. In this way pairs of readings for voltage and charge are obtained. Otherwise an interface connected to a computer can be used to gather the results.

In either case, the graph of Q against V_c is a straight line through the origin.



The charge is directly proportional to the potential difference.

$$Q \ \alpha \ V_c$$

or

$$\frac{Q}{V_c} = \text{constant}$$

The constant is a measure of how much charge the capacitor can store and is called the capacitance (as was mentioned previously). In fact, capacitance is defined as the ratio of Q to V.

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

When Q is given in coulombs and V in volts, C is in farads (F). If the p.d. is one volt when the charge is one coulomb, then the capacitance is one farad. The farad is equivalent to one coulomb per volt.

The farad is a very large unit of capacitance and you will normally come across the microfarad (μF), nanofarad (nF) and picofarad (pF) where

nano = $\times 10^{-9}$
pico = $\times 10^{-12}$

Example

What value of capacitor connected to a 12 V battery would be required to store 53 mC of charge?

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

$$= \frac{53 \times 10^{-3}}{12}$$

$$= 4.4 \times 10^{-3}\ F$$

Example

How much charge is stored by a 220 μF capacitor when connected to a 18 V battery?

$$Q = V \times C$$

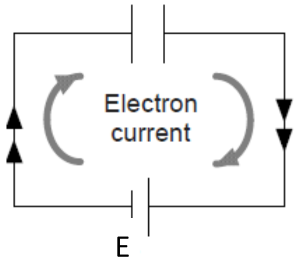
$$= 18 \times 220 \times 10^{-6}$$

$$= 3.96 \times 10^{-3}\ C$$

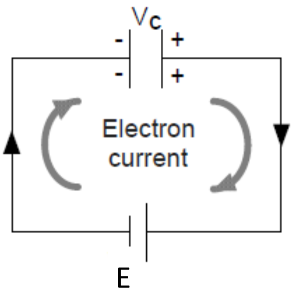
$$= 4.0\ mC$$

Energy Stored in a Capacitor

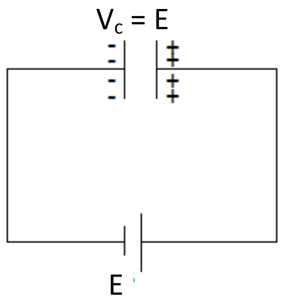
A charged capacitor can be used to light a bulb for a short time, therefore the capacitor must store energy. The charging of a parallel plate capacitor is considered below.



There is an initial surge of electrons from the negative terminal of the cell onto one of the plates (and electrons out of the other plate towards the positive terminal of the cell).

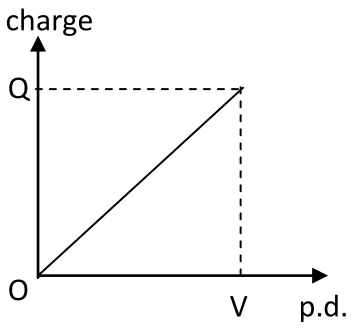


Once some charge is on the plate it will repel more charge and so the current decreases. In order to further charge the capacitor the electrons must be supplied with enough energy to overcome the potential difference across the plates i.e. work is done in charging the capacitor.



Eventually, when the capacitor is fully charged, the current ceases to flow. This happens when the p.d. across the plates of the capacitor is equal to the e.m.f.

Consider a capacitor being charged to a p.d. V and holding a charge Q. The work done in charging a capacitor (the energy stored in a capacitor) is therefore equal to area under the graph of charge against p.d.



$$\text{Area under graph} = \frac{1}{2}QV$$

$$\text{Energy stored} = \frac{1}{2}QV$$

By substituting Q = C V and V = Q/C, two other versions of the equation are obtained:

$$\boxed{E = \frac{1}{2} Q V} \qquad \boxed{E = \frac{1}{2} C V^2} \qquad \boxed{E = \frac{1}{2} \frac{Q^2}{C}}$$

Example

How much energy is available from a capacitor connected to a 12 V battery if the charge stored is 20 mC?

$$E = \frac{1}{2} Q V$$

$$= \frac{1}{2} \times 20 \times 10^{-3} \times 12$$

$$= 120 \times 10^{-3} J$$

$$= 120 \text{ mJ}$$

Example

To what p.d. must a 2200 μF capacitor be charged in order to store 5.0 J of energy?

$$E = \frac{1}{2} C V^2$$

$$5 = \frac{1}{2} \times 2200 \times 10^{-6} \times V^2$$

$$10 = 2200 \times 10^{-6} \times V^2$$

$$4545 = V^2$$

$$V = 67 \text{ V}$$

Conductors, Semi conductors and Insulators

Classifying Materials

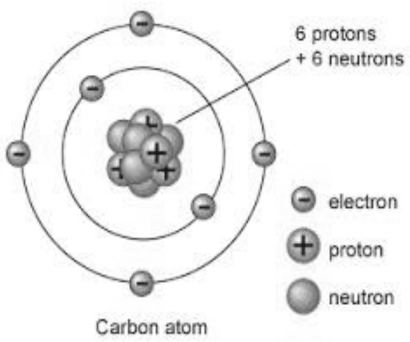
By considering the electrical properties of materials, we can divide them into three groups:

Material	Electrical Properties
Conductors	Materials with many free electrons. These electrons can easily be made to flow through the material. Examples: all metals, semi-metals like carbon- graphite, antimony and arsenic.
Insulator	Materials that have very few free electrons. Examples: plastic, glass and wood.
Semi-conductors	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.

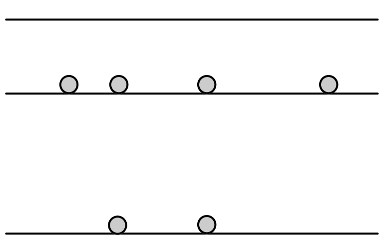
Band Structure

An atom consists of a positively charged nucleus containing protons and neutrons with electrons orbiting. In an isolated atom the electrons occupy *discrete energy levels*.

Discrete energy levels

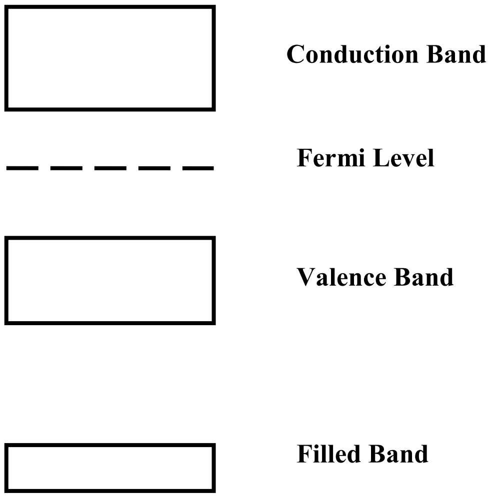


Simple energy level diagram for the isolated atom opposite



Each level can hold a certain number of electrons. There can be many energy levels, but no electrons can exist in the gap between the levels.

When atoms are close to each other the electrons can use the energy levels of their neighbours. However, when the atoms are arranged in a crystalline lattice of a solid, the electrons in adjacent atoms cannot occupy the same energy levels, so the energy levels of the isolated atoms are split into many levels of slightly different energy. These energy levels are so closely spaced that they form a continuous band of permitted energy levels. Thus, in a solid, the electrons occupy a continuous range of allowed energy levels rather than a single level for an isolated atom.



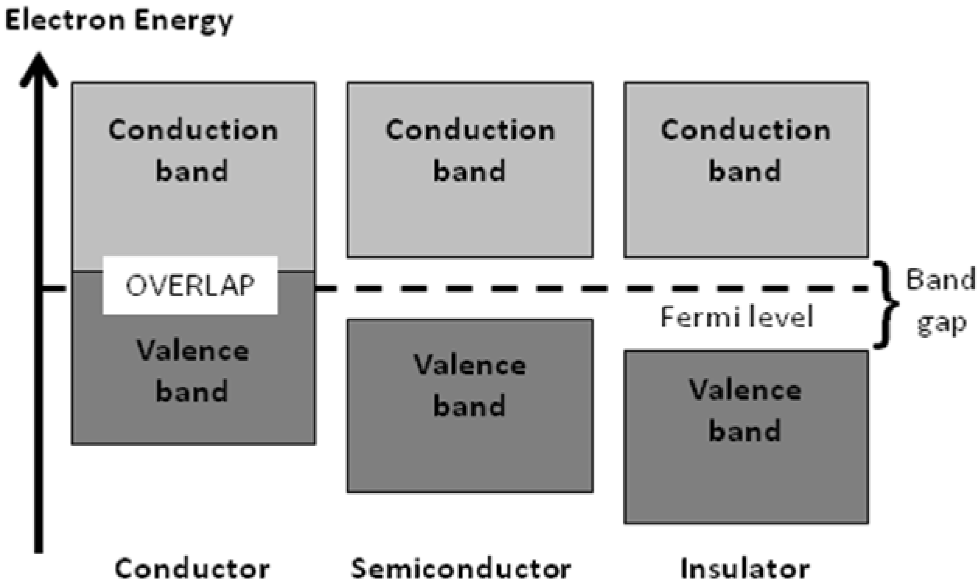
There will also be a group of energy levels that are not allowed. These occur between the bands in what is known as the *band gap*.
Similar to the energy levels of an individual atom, the electrons in a solid will fill the lower bands first. The Fermi level gives a rough idea of the energy level which electrons will generally fill up to, but there will always be some electrons with individual energies above this.

The Fermi level is not mentioned in the Higher content statements but is an important concept to aid understanding of electrical properties of solids, and is often seen in diagrams representing the energy bands in solids.

The Fermi level is the maximum permitted energy an electron in a specific structure can possibly have at a temperature of absolute zero. At room temperature, it is possible for electrons to have higher energies. Thus changes in structure can change the Fermi level.

Electrical Conduction in Conductors, Insulators and Semiconductors

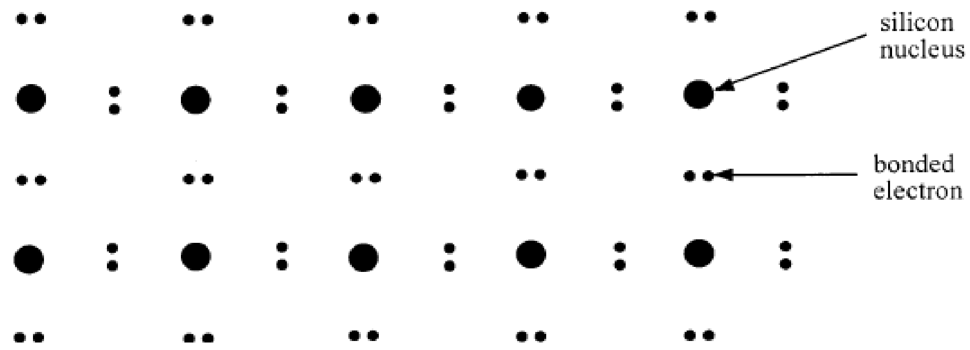
Band theory allows us to understand the electrical properties of conductors, insulators and semiconductors.



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 valence 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

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.

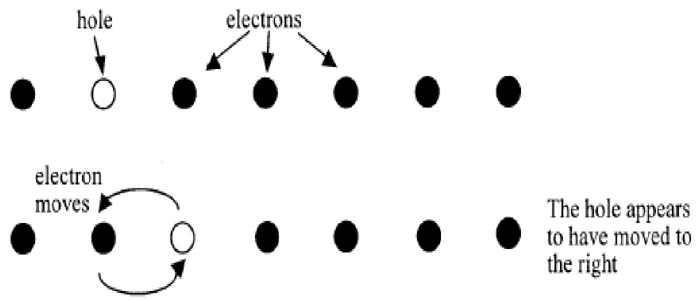


Imperfections in the crystal lattice and thermal ionisation due to heating can cause a few electrons to become free. A higher temperature will result in more free electrons, increasing conductivity and thus decreasing the resistance e.g. as in a thermistor.

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.

Thus, small currents consist of drifting electrons in one direction and holes in the other.

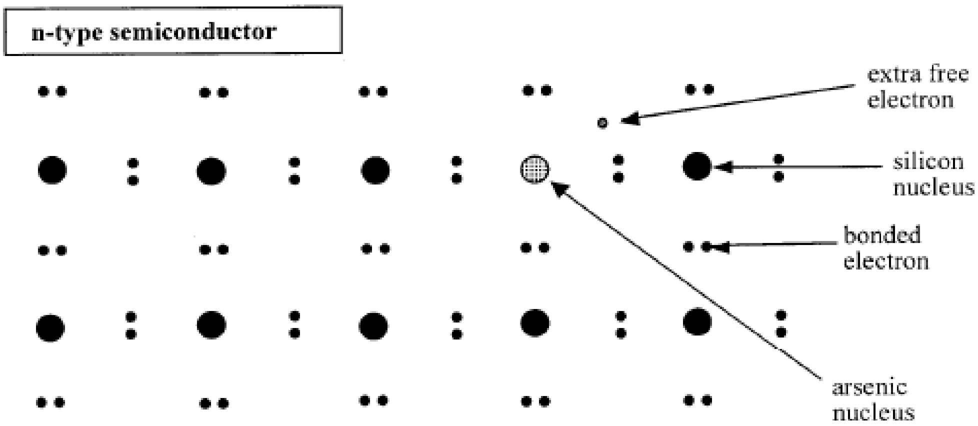
Doping

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

In such devices, the electrical properties are dramatically changed by the addition of very small amounts of impurities . This is known as ***doping***. This action reduces the resistance of the semiconductor and increases its conductivity.

n –type semiconductors

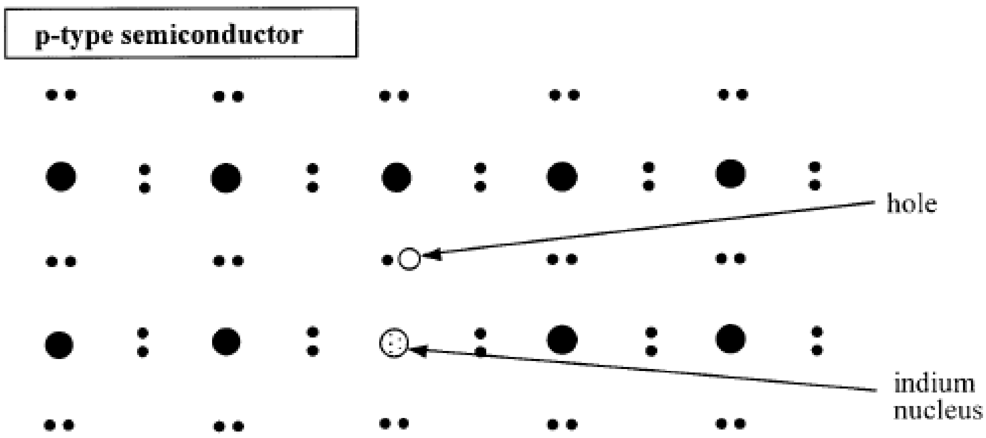
If an impurity such as arsenic (As), which has five outer electrons, is present in the crystal lattice, then four of its electrons will be used in bonding with the silicon. The fifth will be free to move about and conduct. Since the ability of the crystal to conduct is increased, the resistance of the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

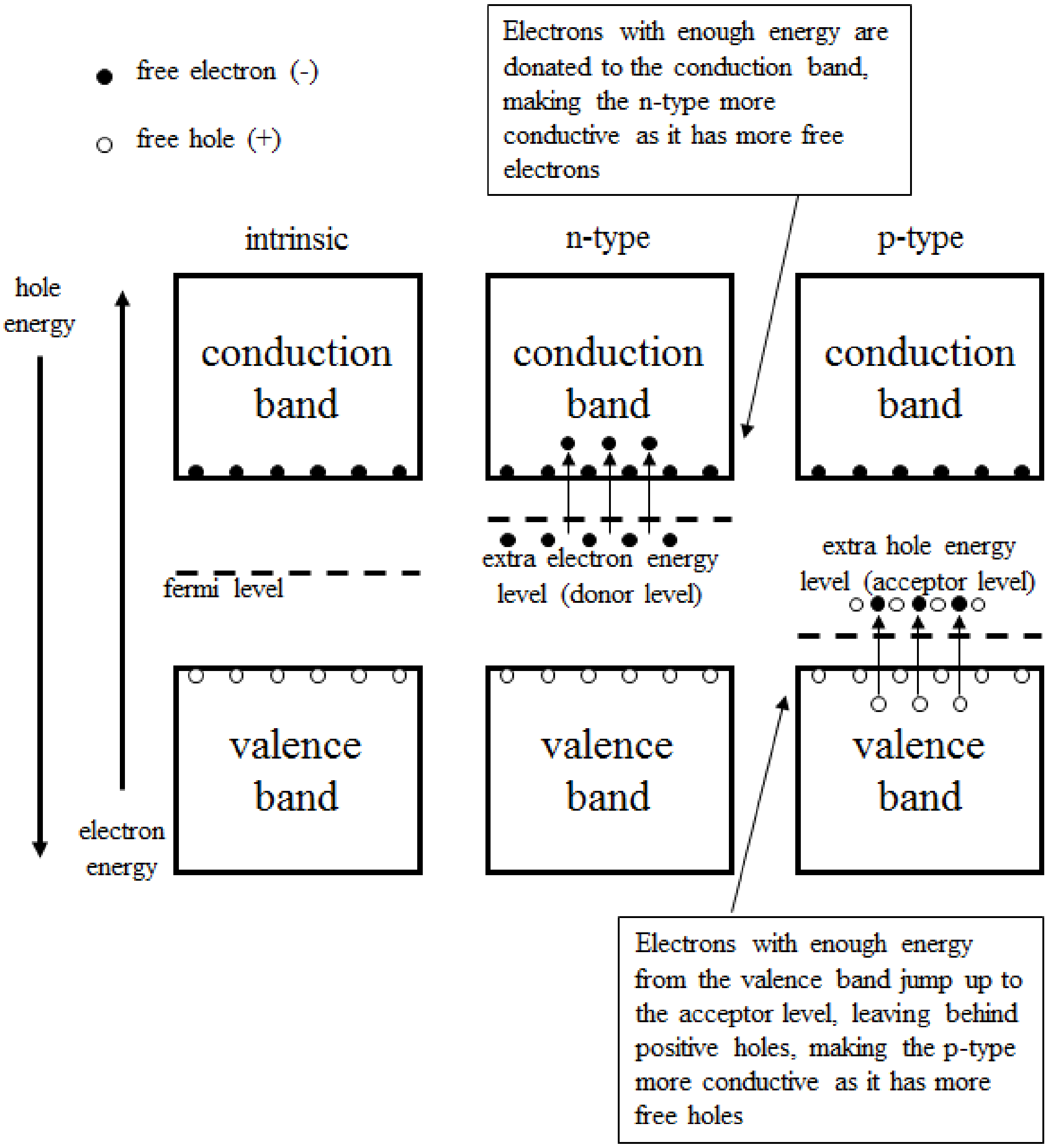


An electron from the next atom can move into the hole created as described previously. Conduction can thus take place by the movement of positive holes. This is called a *p-type* semiconductor, as most conduction takes place by the movement of positively charged 'holes'.

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 valence band.

The majority of charge carriers are electrons in n-type and holes in p-type. (However, there will always be small numbers of the other type of charge carrier, known as minority charge carriers, due to thermal ionisation.)



n-type

In n-type, the added impurities introduce free electrons to the structure, which exist in an isolated energy level in the band gap (<u>called the donor level</u>), near the conduction band (see diagram on previous page).

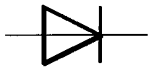
The fermi level is now raised just above this energy, because of the doping, and at room temperatures, these electrons can gain enough energy to jump into the conduction band and contribute to conduction.

p-type

In p-type, the added impurities introduce holes to the structure, which exist in an isolated energy level in the band gap (<u>called the acceptor level</u>), near the valence band (see diagram on previous page).

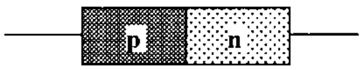
The fermi level is now lowered to just below this energy, and at room temperatures, electrons in the valence band can gain enough energy to jump into these holes, leaving holes in the valence band which aid conduction there.

The p –n Junction Diode



circuit symbol

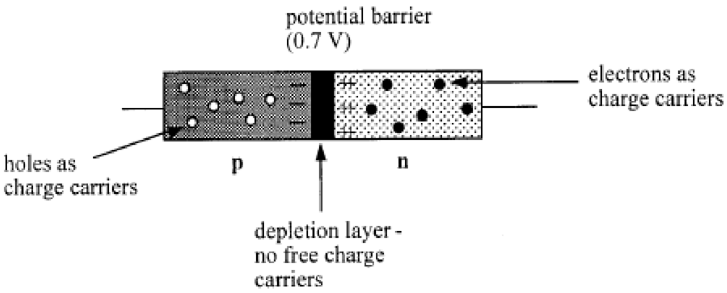
When a semiconductor is grown so that one half is p-type and the other half is n-type, the product is called a p-n junction and it functions as a diode.



At temperatures above absolute zero, the electrons in the n-type material and the holes in the p-type material will constantly diffuse. The charge carriers near the junction will be able to diffuse across it in opposite directions. (Diffusion is the spread of any particles through random motion from high concentration regions to low concentration regions)

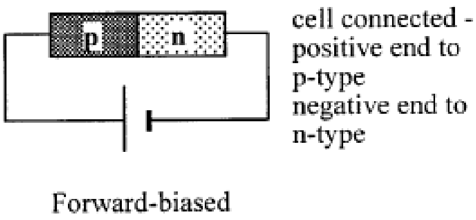
Some of the free electrons from the n- type material diffuse across the junction and fill some of the holes in the p- type material. This can also be thought of as holes moving in the opposite direction to be filled with electrons.

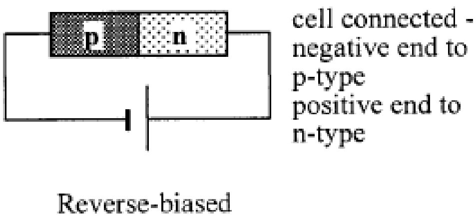
Since the n-type has lost electrons, it becomes positively charged near the junction. The p-type having gained electrons becomes negatively charged. There will be a small voltage, a potential barrier (about 0.7 V in silicon), across the junction due to this charge separation. This voltage will tend to 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*.



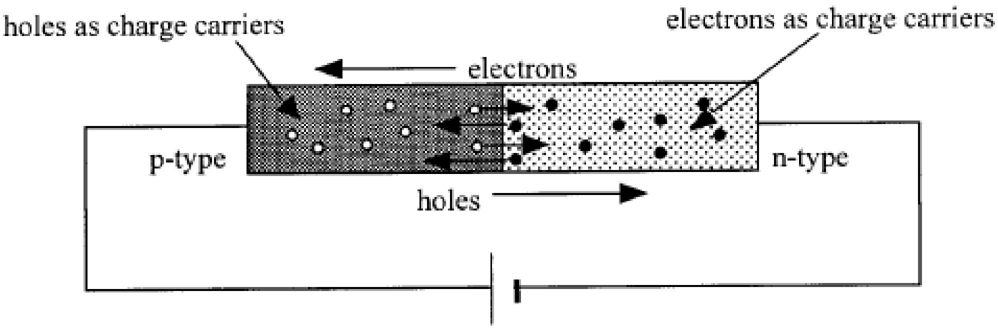
Biasing the Diode

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



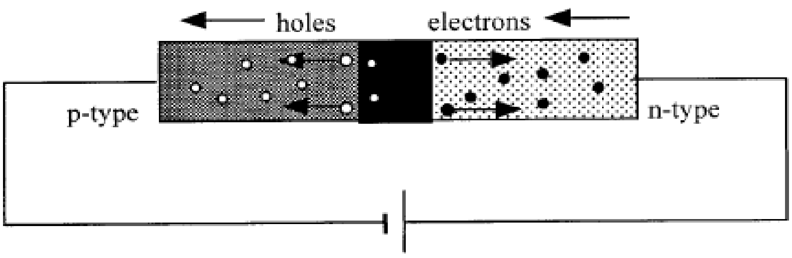


The Forward – Biased Diode



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). The electrons are attracted to the positive battery terminal, flow through the junction and move 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 and the depletion layer disappears.

The Reverse – Biased Diode

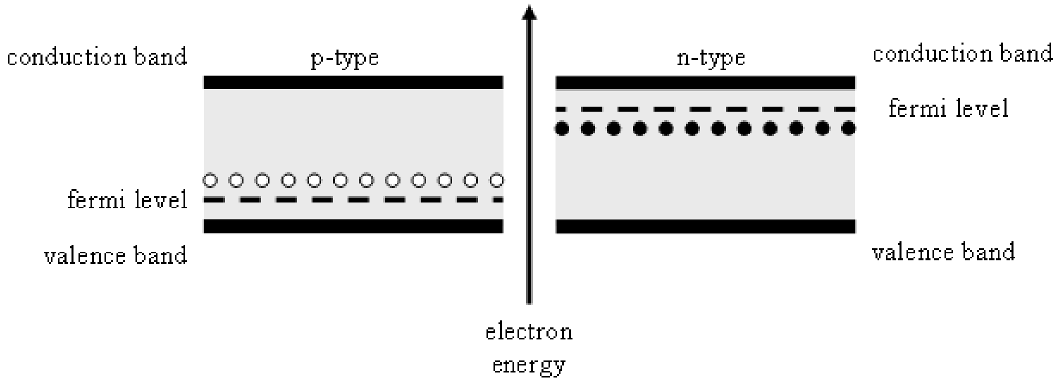


When the cell is connected as above, the applied potential causes the depletion layer to increase in width thus increasing the size of the potential barrier. This happens because electrons in the n-type move away from the junction as they are attracted to the positive battery terminal. Similarly, the holes move in the opposite direction. Almost no conduction can take place.

There is a very small current, known as the reverse or leakage current.

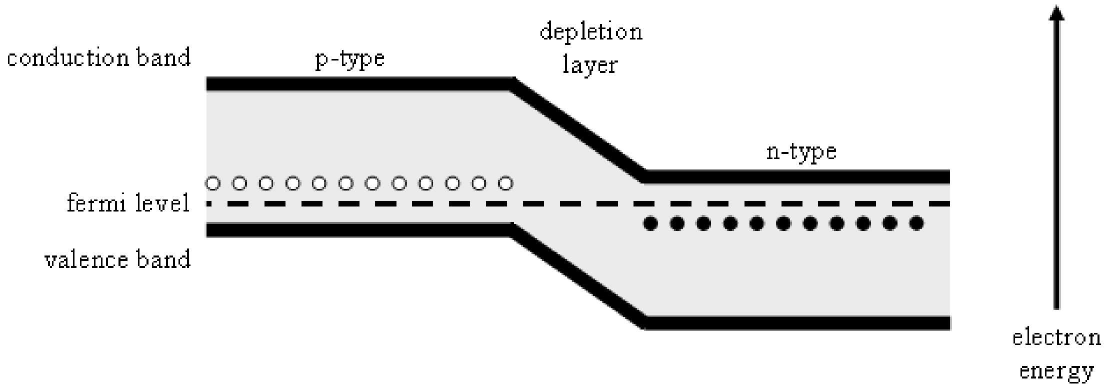
p-n Junctions and Band Structure

To understand p-n junctions, it is helpful to look at what is happening to the energy bands when they are grown together.



p-n Junction Diode with no Bias Applied

When a p-type semiconductor is joined with a n-type semiconductor, the Fermi level remains flat throughout the device. This means that the conduction and valence bands must be higher in the p-type than in the n-type.



With no bias applied (i.e. the diode is not connected to a battery or other electrical energy source), the electrons in the n-type require energy to travel through the depletion layer, against the potential barrier. The upward direction in the diagram represents increasing energy. In other words, the electrons need energy to move uphill, energy which can be supplied by an electrical energy source.

Why does the fermi level remain flat?

Diffusion takes place at the junction.

The doped n-type and p-type materials become more like intrinsic (undoped) semiconductors the closer they are to the junction.

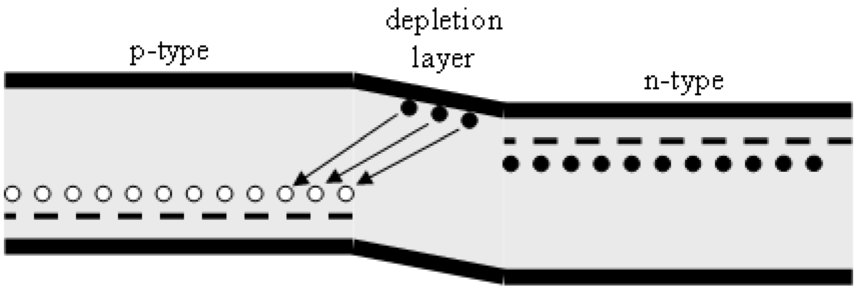
The Fermi level is in the middle of the band gap for an intrinsic semiconductor. (See previous band theory diagrams).

Hence the n-type and p-type energy bands adjust to keep the Fermi level in the middle at the junction.

Once you bias the junction (apply a voltage across it) the Fermi level is no longer flat.

Forward Biased

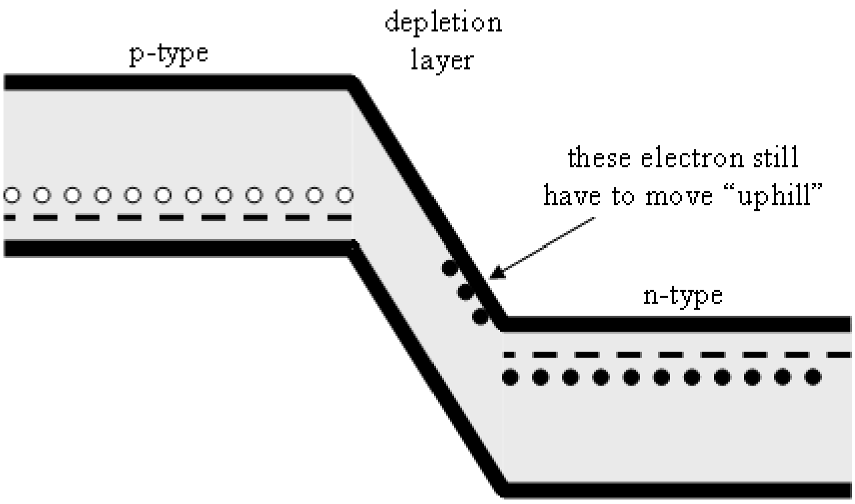
By applying a forward bias (positive voltage) to the diode the difference between the energy bands is reduced, and current can flow more easily. The diode conducts in forward bias.



The electrons in the n-type material which have been elevated to the conduction band and which have diffused across the junction find themselves at a higher energy than the holes in the p-type material. They readily combine with those holes, making possible a continuous forward current through the junction.

Reverse Biased

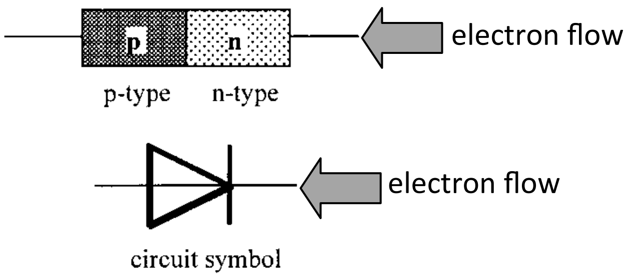
By applying a reverse bias (negative voltage) the potential barrier (energy the electrons require to pass through the depletion layer) is increased. The diode does not conduct in reverse bias.



The electrons in the n-type material which have been elevated to the conduction band and which have diffused across the junction are still at a lower energy than the holes in the p-type material. A forward current is not possible.

Current Flow in p-n Junctions

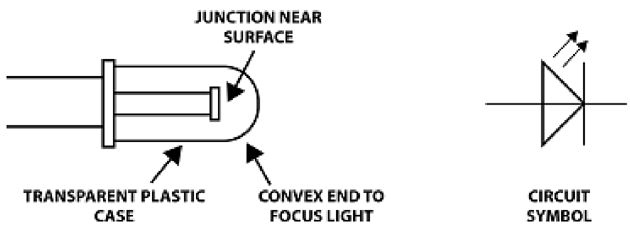
In conclusion, a p-n junction will only allow current to flow through it one way, as indicated below.



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.



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

For each recombination of electron and hole, one photon of radiation is emitted.

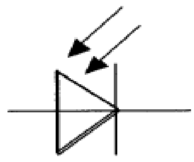
Depending on the type of semiconductor used the radiation may be in the form of heat resulting in a temperature increase. However, in some semiconductors such as gallium arsenic phosphide, the energy is emitted as photons of light. The colour of the emitted light depends on the relative amounts of gallium, arsenic and phosphorous used to produce the semiconductor.

The frequency of light from an LED is controlled by the size of the energy gap between the conduction and valence bands. A bigger gap will result in a larger energy change and a higher frequency of light being emitted.

The recombination energy can be calculated using **E = h f,** if the frequency is known.
[As discussed previously, the diode does not conduct in reverse bias, therefore an LED will not work when connected in reverse bias.]

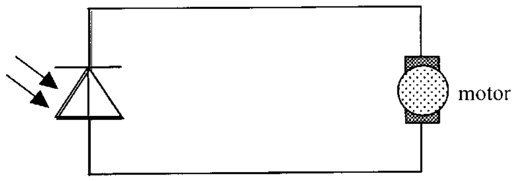
The Photodiode

A p-n junction in a transparent coating will react to light. The photodiode can be used in two modes; *photovoltaic mode* and *photoconductive mode*.



Photovoltaic Mode

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



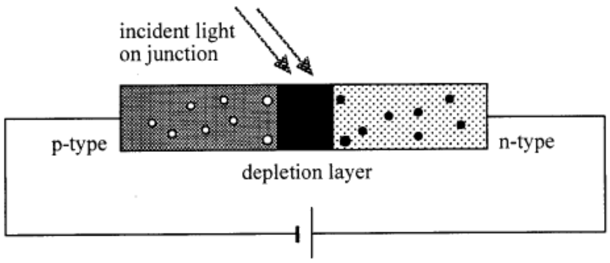
Photons that are incident on the junction have their energy absorbed, freeing electrons and creating electron-hole pairs. A voltage is generated by the separation of the electron and hole.

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. The voltage generated is proportional to the light intensity.

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 light shines on the junction, electrons are freed and electron-hole pairs are created. 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)**.