Unit 3 - Electricity

MONITORING and MEASURING A.C.

1. a.c. as a current which changes direction and instantaneous value with time.
2. Calculations involving peak and r.m.s. values
3. Monitoring a.c. signals with an oscilloscope, including measuring frequency, and peak and r.m.s. values
4. Determination of frequency, peak voltage and r.m.s. from graphical data

CURRENT, VOLTAGE, POWER and RESISTANCE

5. Current, voltage and power in series and parallel circuits.
6. Calculations involving potential difference, current, resistance and power (may involve several steps)
7. Carry out calculations involving potential dividers circuits.

ELECTRICAL SOURCES and INTERNAL RESISTANCE

8. Electromotive force, internal resistance and terminal potential difference.
9. Ideal supplies, short circuits and open circuits.
10. Determining internal resistance and electromotive force using graphical analysis.

CAPACITORS

11. Capacitors and the relationship between capacitance, charge and potential difference.
12. The total energy stored in a charged capacitor is the area under the charge against potential difference graph.
13. Use the relationships between energy, charge, capacitance and potential difference.
14. Variation of current and potential difference against time for both charging and discharging.
15. The effect of resistance and capacitance on charging and discharging curves.

CONDUCTORS, SEMICONDUCTORS and INSULATORS

16. Solids can be categorised into conductors, semiconductors or insulators by their ability to conduct electricity.

17. The electrons in atoms are contained in energy levels. When the atoms come together to form solids, the electrons then become contained in energy bands separated by gaps.

18. In metals which are good conductors, the highest occupied band is not completely full and this allows the electrons to move and therefore conduct. This band is known as the conduction band.

19. In an insulator the highest occupied band (called the valence band) is full. The first unfilled band above the valence band is the conduction band.

20. For an insulator the gap between the valence band and the conduction band is large and at room temperature there is not enough energy available to move electrons from the valence band into the conduction band where they would be able to contribute to conduction.

21. There is no electrical conduction in an insulator.

22. In a semiconductor the gap between the valence band and conduction band is smaller and at room temperature there is sufficient energy available to move some electrons from the valence band into the conduction band allowing some conduction to take place. An increase in temperature increases the conductivity of a semiconductor.

P-N JUNCTIONS

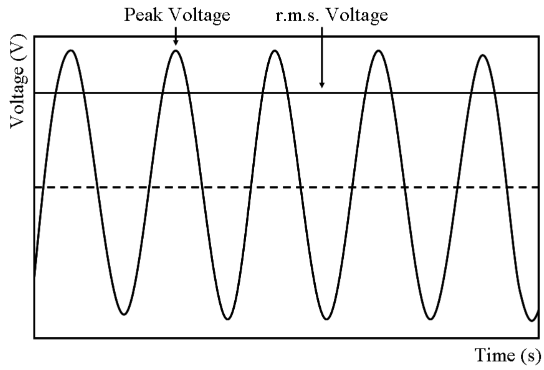
23. During manufacture, the conductivity of semiconductors can be controlled, resulting in two types: p-type and n-type.

24. When p-type and n-type material are joined, a layer is formed at the junction. The electrical properties of this layer are used in a number of devices.

25. Solar cells are p-n junctions designed so that a potential difference is produced when photons enter the layer. This is the photovoltaic effect.

26. LEDs are forward biased p-n junctions diodes that emit photons when a current is passed through the junction.

A.C. / D.C.



This graph displays the a.c. and d.c. potential differences required to provide the same power to a given component. As can be seen the a.c. peak is higher than the d.c. equivalent. The d.c. equivalent is known as the root mean square voltage or V_{rms}. Similarly the peak current is related to the root mean square current.

Relationships between the a.c. peak and the root mean square for both voltage and current are given below.

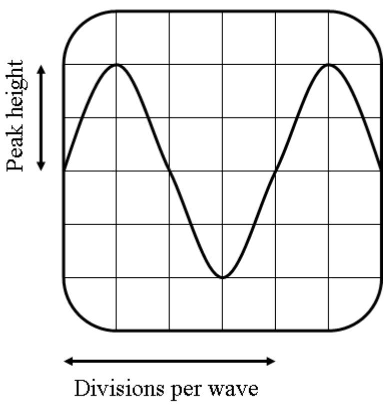
$$V_{peak} = \sqrt{2}V_{rms}$$
$$I_{peak} = \sqrt{2}I_{rms}$$

$$\text{frequency} = \frac{1}{\text{Period}}$$
$$f = \frac{1}{T}$$

In the U.K., the mains voltage is quoted as 230 V a.c. - This is the r.m.s. value. It also has a frequency of 50Hz.

The mains voltage rises to a peak of approximately 325 V a.c.

Using a cathode ray oscilloscope (C.R.O.) to measure peak voltage and frequency of an a.c. supply



Two of the main controls on a cathode ray oscilloscope (C.R.O.) are the Y GAIN and the TIME BASE.

In this case we take Y gain to be 3V cm^{-1} and the timebase to be 5ms cm^{-1}.

The screen is covered with a square grid - The squares are usually 1 cm across.

An a.c. voltage can be displayed on the screen by connecting an a.c. supply to the Y INPUT terminals.

Calculating Peak Voltage

Peak voltage = peak height x Y gain setting

= 2 cm x 3 V cm^{-1}

= 6V

Calculating Frequency

Period = divisions per wave x timebase

= 4 cm x 5 ms cm^{-1}

= 20ms = 20 x 10^{-3}s

Frequency = 1/T = 1/20x10^{-3}
= 50 Hz

Current (A) - Rate of flow of charge

Current is the rate of flow of charge in a circuit and can be calculated using

$$Q = It$$

Q - quantity of charge, measured in coulombs (C)
I - current, measured in amps (A)
t - time, measured in seconds (s)

In a complete circuit containing a cell, a switch and a bulb the free electrons in the conductor will "experience a force which will cause them to move drifting away from the negatively charged end towards the positively charged end of the cell".

Electrons are negatively charged.

1 electron = (-)1.6×10^{-19} Coulomb
1 Coulomb = 6.25×10^{18} electrons

Potential Difference (V)

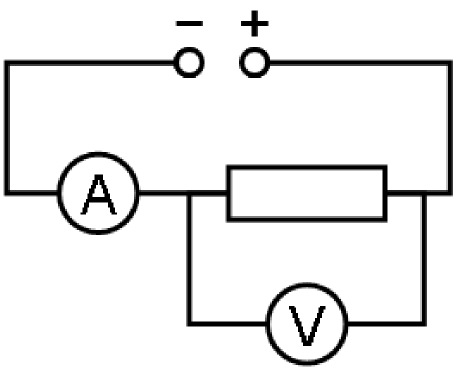
If one joule of work is done in moving one coulomb of charge between two points then the potential difference (p.d.) between the two points is 1 volt. (This means that work is done when moving a charge in an electric field)

$$E_W = QV$$

E_w - work done moving charge betwenn 2 points, measured in joules (J)
Q - quatity of charge, coulombs (C)
V - Potential difference between 2 points in an electric field, joules per coulomb (JC^{-1}) or volts (V)

When energy is transferred by a component (eg electrical to light and heat in a bulb) then there is a potential difference (p.d) across the component.

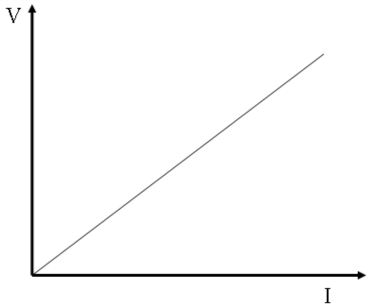
Using Ammeters and Voltmeters



Ammeters are connected in series with components and measure the current (I) in amperes (A).

Voltmeters are connected in parallel (across a component) and measure the potential difference (V) in volts (V).

Ohm's Law



At a constant temperature for a given resistor we find that the current through the rsistor is proportional to the voltage across it. the ratio of V/I is equal to a constant. This constant is known as resistance (R), which is measured in ohms (Ω).

$$V = IR$$

V - Voltage across resistor, measured in volts (V)
I - Current through resistor, measured in amps (A)
R - Resistance of resistor, measured in ohms, (Ω)

Example
Calculate the resistance of a 15V light bulb if 2.5mA of current passes through it.

$$V = IR$$
$$15 = 2.5\times10^{-3}\times R$$
$$R = \frac{15}{2.5\times10^{-3}}$$
$$R = 6000\Omega$$

Ohmic resistors have a steady resistance, which is maintained because they can disperse their heat. There are components which do not have a constant resistance as the current flowing through them is altered – eg a light bulb. Graphs of potential difference against current for this type of component will not be a straight line. These components are said to be non-ohmic, as their resistance changes with temperature.

Resistance (Ω)

Resistors can be combined in series or in parallel. In any circuit there may be multiple combinations of resistors in both series and parallel, any combination of resistors will have an effective total resistance.

Series Resistance: $$R_T = R_1 + R_2 + ...$$

Parallel Resistance: $$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + ...$$

Power (W) - rate of transformation of energy

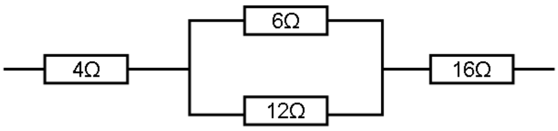
The power of a circuit component (such as a resistor) tells us how much electrical potential energy the component transforms (changes into other forms of energy) every second:

The following formulae are also used to calculate power (P):

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

<u>Examples</u>

Determine the total resistance of the following resistor combinations.



<u>Step 1</u> - Parallel section first:

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

$$\frac{1}{R_T} = \frac{1}{6} + \frac{1}{12} = \frac{2}{12} + \frac{1}{12} = \frac{3}{12}$$

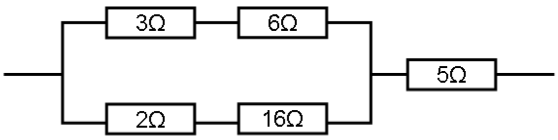
$$R_T = \frac{12}{3} = 4\Omega$$

<u>Step 2</u> - Total Resistance:

$$R_T = R_1 + R_2 + R_3$$

$$R_T = 4 + 4 + 16$$

$$R_T = 24\Omega$$



<u>Step</u> 1 - Simplify the branches

Branch 1

$$R_T = R_1 + R_2$$

$$R_T = 3 + 6 = 9\Omega$$

Branch 2

$$R_T = R_1 + R_2$$

$$R_T = 2 + 16 = 18\Omega$$

<u>Step 2</u> - Parallel section

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

$$\frac{1}{R_T} = \frac{1}{9} + \frac{1}{18} = \frac{2}{18} + \frac{1}{18} = \frac{3}{18}$$

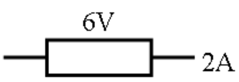
$$R_T = \frac{18}{3} = 6\Omega$$

<u>Step 3</u> - Final series addition

$$R_T = R_1 + R_2$$

$$R_T = 6 + 5 = 11\Omega$$

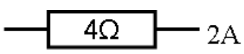
In each case, calculate the <u>power</u> of the resistor.



$$P = IV$$

$$P = 2 \times 6$$

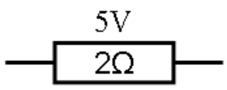
$$P = 12W$$



$$P = I^2R$$

$$P = 2^2 \times 4$$

$$P = 16W$$



$$P = V^2/R$$

$$P = 5^2 \times 2$$

$$P = 12.5W$$

<u>Potential Dividers (Voltage Dividers)</u>

Any circuit that contains more than one component can be described as a potential divider circuit. In its simplest form a potential divider is 2 resistors connected across a power supply. If another component is placed in parallel with a section of the potential divider circuit, the operating potential difference of this component can be controlled.

The p.d. across each resistor is in proportion to the resistance in the circuit. In a circuit with a 6Ω and a 12 Ω resistor, the 12 Ω resistor has 2/3 of the total resistance, and therefore 2/3 of the total p.d. is across this resistor.

Potential Dividers - Useful Equations

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

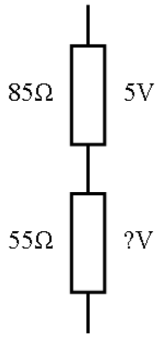
$$V_1 = \left(\frac{R_1}{R_1 + R_2}\right)V_S$$

V_1 - Voltage across resistor 1
V_2 - Voltage across resistor 2
V_S - Supply voltage

R_1 - Resistance of resistor 1
R_2 - Resistance of resistor 2

Example

Find the missing voltage:



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

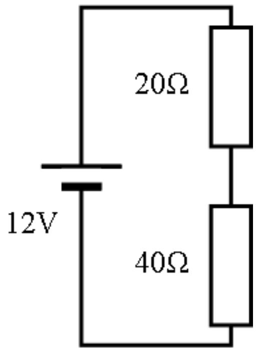
$$\frac{5}{V_2} = \frac{85}{55}$$

$$\frac{5}{V_2} = 1.55$$

$$V_2 = \frac{5}{1.55}$$

$$V_2 = 3.24\text{V}$$

Find the voltage across R_2:



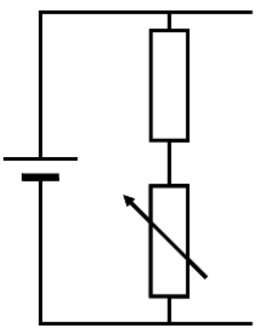
$$V_2 = \left(\frac{R_2}{R_1 + R_2}\right)V_S$$

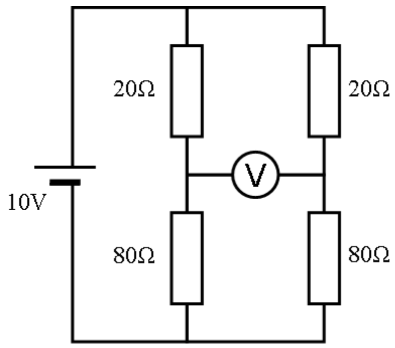
$$V_2 = \left(\frac{40}{20 + 40}\right)\times 12$$

$$V_2 = 8V$$

Potential Dividers as voltage controllers

If a variable resistor is placed in a potential divider circuit then the voltage across this resistor can be controlled.

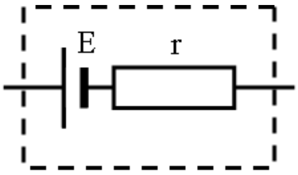




Alternatively, two potential dividers can be connected in parallel. A voltmeter is connected between the two dividers. Resistors can be chosen such that there is different electrical potential at point A and B. This p.d. can be controlled by altering the resistors.

The potential at point A is 8V
The potential at point B is 5V
The reading on the voltmeter is 8 - 5 = 3V

Internal Resistance (r) of a Cell



Symbol for internal resistor

Resistance is the opposition to the flow of electrons. When electrons travel through a cell, the cell itself opposes their motion - so every cell has a resistance known as its internal resistance (r).

A cell can be thought of as a source of emf (E) in series with an internal resistor (r).

electromotive force (emf)

When energy is being transferred from an external source (like a battery) to the circuit then the voltage is known as the emf.

DEFINITION
The emf of a source is the electrical energy supplied to each coulomb of charge which passes through the source (i.e. a battery of emf 6V provides 6 J/C)

Therefore, the emf is the maximum voltage a source can provide.

How to measure the emf of a cell

The emf of a new cell is the "voltage value" printed on it. To find the emf of a cell, we connect a high resistance voltmeter across its terminals when no other components are connected to it. Because the voltmeter has a high resistance, no current is taken from the cell - When no current flows, we have an open circuit.

In other words, the emf is the voltage of the battery when no current is drawn:
"the emf of the cell is the open circuit potential difference (p.d.) across its terminals."

Lost Volts

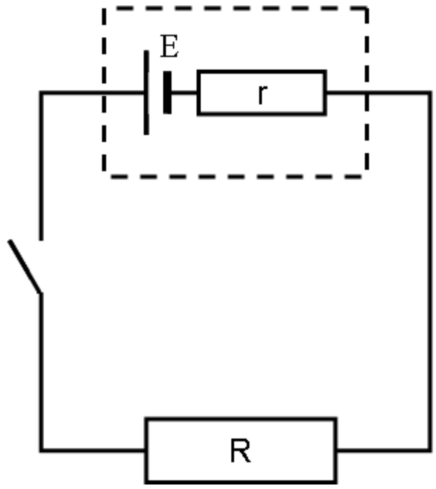
A cell has internal resistance therefore potential difference (voltage) is lost across it (turned into heat) when the cell is connected to a circuit. The LOST VOLTS are not available to the components in the circuit.

Terminal Potential Difference (tpd)

As a result of LOST VOLTS, the potential difference (voltage) a cell is able to supply to components in a circuit is called its TERMINAL POTENTIAL DIFFERENCE (t.p.d.)

This is the potential difference (voltage) across the cell terminals when it is connected in a circuit.

An electric circuit can be simplified to the form shown below. The circuit consists of a cell with e.m.f. (E) and internal resistance (r) connected to an external resistor (R) through a switch. There is an electric current (I) in the circuit when the switch is closed.



When the switch is open, a voltmeter connected across the cell terminals will show the cell emf. This is because there is no current flowing and therefore there are no lost volts across the internal resistor.

When the switch is closed, a voltmeter connected across the cell terminals will show the cell tpd. This is because there is now a current flowing and therefore there are lost volts across the internal resistor.

The emf is the sum of the terminal potential difference and the lost volts.

The circuit is essentially a potential divider. If the tpd is large, the lost volts will be small.

When R is large, the current draw is small, so the lost volts will be small and the tpd will be close to the emf

$$E = IR + Ir$$

$$E = V + Ir$$

E - emf of the cell (V)
R - Total external resistance (R)
V = IR - Terminal potential difference (V)

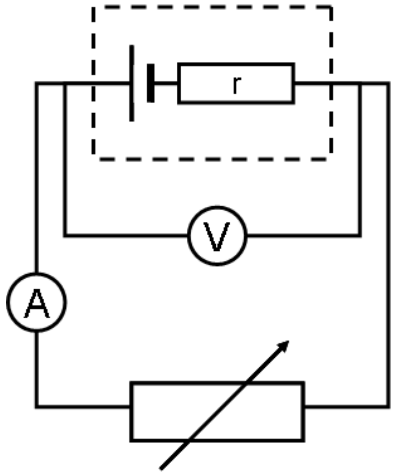
I - circuit current (A)
r - internal resistance (R)
v = Ir - lost volts (V)

Short circuit current

When the 2 terminals of a cell are connected together with just a wire, which has (almost) zero resistance, we say the cell has been SHORT CIRCUITED.

- The external resistance (R) = 0. In this case: E = Ir
- I is known as the short circuit current
- If r is small (usually the case) then I will be large
- This is dangerous, the cell will heat up as electrical energy is converted to heat due to the internal resistance.

Determine the Internal Resistance



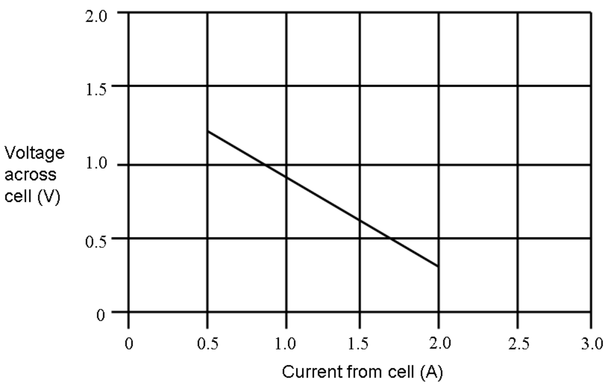
It is possible to find the emf and internal resistance of a power supply using the circuit shown. The load resistance is altered and the corresponding current and tpd values are recorded.

A graph of tpd versus current is plotted.

By rearranging the formula E = V + Ir in the form y = mx + c we can find both the emf and internal resistance of the cell:

$$y = m x + c$$
$$V = -r I + E$$

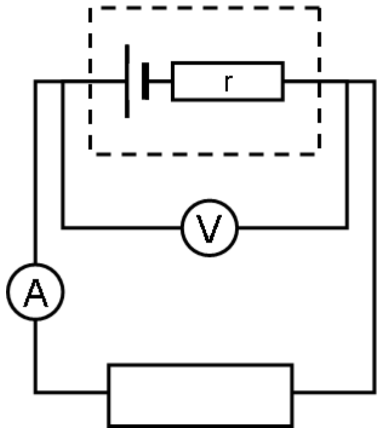
The gradient m = -r
The y-intercept c = E



$$y - \text{intercept} = \text{emf} = 1.5\text{V}$$
$$\text{Gradient} = -\text{r}$$
$$\text{Gradient} = \frac{\text{change in y}}{\text{change in x}}$$
$$\text{Gradient} = \frac{-0.5}{0.85} = -0.59$$
$$\text{Internal resistance} = 0.59\Omega$$

<u>Example</u>

In this circuit, when the switch is open, the voltmeter reads 2.0 V. When the switch is closed, the voltmeter reading drops to 1.6 V and a current of 0.8 A flows through resistor R.



(a) State the value of the cell emf
(b) State the terminal potential difference across R when the switch is closed.
(c) Determine the 'lost volts' across the cell.
(d) Calculate the resistance of resistor R.
(e) Calculate the internal resistance of the cell.

(a) 2.0V (b) 1.6V

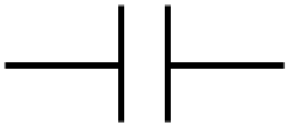
(c) $E = \text{tpd} + \text{lost volts}$
$2.0 = 1.6 + \text{lost volts}$
$\text{lost volts} = 0.4\text{V}$

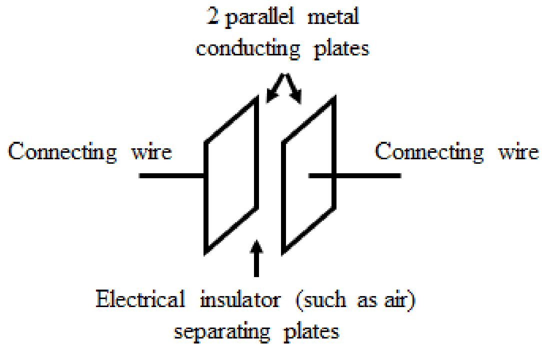
(d) $\text{tpd} = \text{IR}$
$1.6 = 0.8 \times \text{R}$
$\text{R} = 2\Omega$

(e) $\text{lost volts} = \text{Ir}$
$0.4 = 0.8 \times \text{r}$
$\text{R} = 0.5\Omega$

Capacitors - Capacitance, Charge and Potential Difference

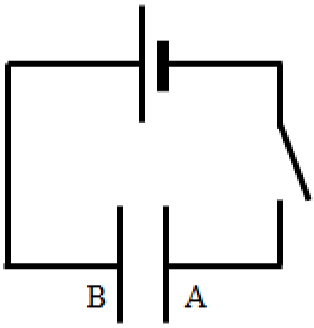
Capacitors are very important components in electrical devices. They store electrical energy by allowing a charge distribution to accumulate on two conducting plates. The ability to store this charge distribution is known as capacitance.





A simple capacitor consists of 2 parallel metal conducting plates separated by an electrical insulator such as air. The circuit symbol for a capacitor is shown above.

To energise a capacitor, we connect a battery (or d.c. power supply) across its conducting plates. When the switch is closed, electrons flow onto plate A, and away from plate B, thus creating a charge distribution.

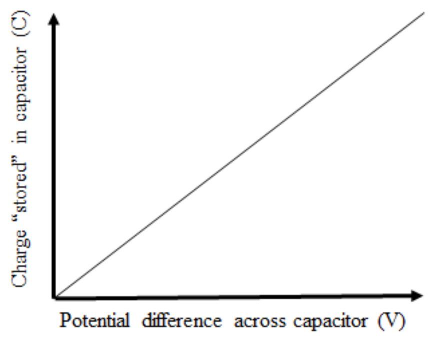


Electric charge is now stored on the conducting plates.

This creates a potential difference across the conducting plates which increases until it becomes equal to the battery/supply voltage.

The higher the potential difference (V) across the conducting plates, the greater the charge (Q) distribution between the plates. The charge (Q) stored on the 2 parallel conduction plates is directly proportional to the potential difference (V) across the plates. The constant, which equals the 'ratio of charge to potential difference', is called the capacitance of the capacitor.

A graph of charge versus potential difference for a capacitor illustrates the direct proportionality between charge and pd. The gradient of this line (the ratio between Q and V) is defined as the capacitance (C) of the capacitor. This leads to the relationship below.



$$Q = CV$$

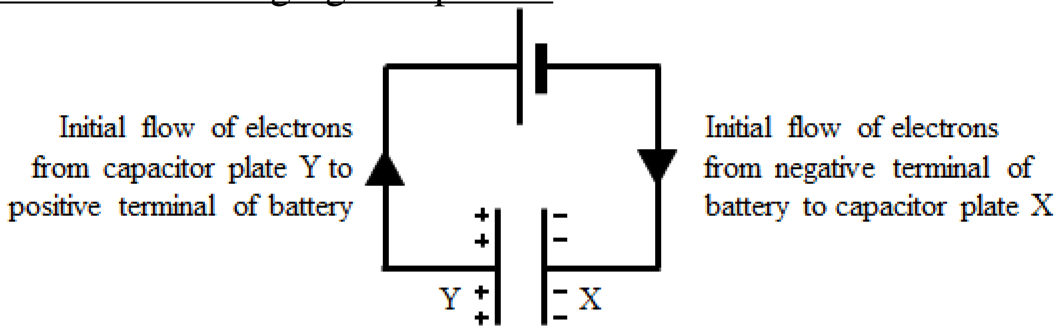
Q – charge "stored" in capacitor, measured in coulombs (C)
C – capacitance of capacitor, measured in Farads (F)
V – potential difference across capacitor, measured in volts (V)

Note about the Farad

The farad is a very large unit - Too large for the practical capacitors used in our household electronic devices (televisions, radios, etc). These practical capacitors have smaller "sub-units":

microfarads (μF) …$\times 10^{-6}$F nanofarads (nF) …$\times 10^{-9}$F picofarads (pF)…10^{-12}F

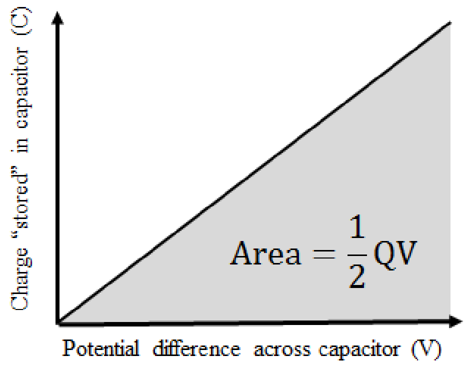
Work Done Charging a Capacitor



To push electrons onto the negatively charged plate, the battery must do work against the potential difference between the capacitor plates.

WORK MUST BE DONE TO CHARGE A CAPACITOR

The work done charging a capacitor equals the area under the QV graph for charging a capacitor.



Energy stored in a capacitor

Work done by a battery/power supply in charging is stored as electrical potential energy in an electric field which exists between the charged capacitor plates. The electrical potential energy is released when the capacitor is discharged, e.g. by connecting both plates of the capacitor to a light bulb.

Equations for energy stored in a capacitor

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

E – energy stored in capacitor, joules (J)
Q – charge "stored" in capacitor, coulombs (C)
V – potential difference across capacitor, volts (V)
C – capacitance of capacitor, Farads (F)

Examples

Calculate the energy stored in a 15V capacitor with a stored charge of 2.0 x 10^{-6}C

E = 1/2 QV
E = 0.5 x 2.0 x 10^{-6} x 15
E = 1.5 x 10^{-5}J

Calculate the charge stored on the plates of a capacitor with 6.0 x 10^{-3} J of energy and a capacitance of 3 micro Farads.

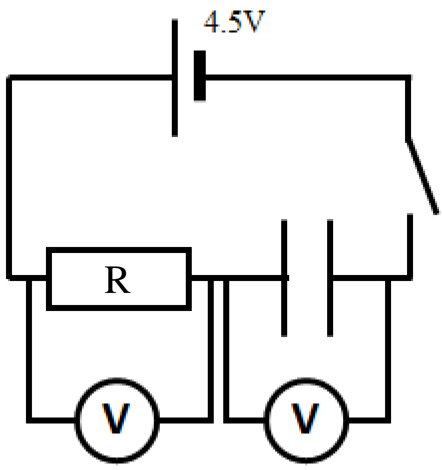
$$E = \frac{1}{2}\frac{Q^2}{C}$$

$$6.0\times10^{-3} = \frac{0.5\times Q^2}{3\times10^{-6}}$$

$$Q^2 = 3.6\times10^{-8}$$

$$Q = 1.9\times10^{-4}\,C$$

Investigating a charging capacitor



This electric circuit can be used to investigate the charging of a capacitor.

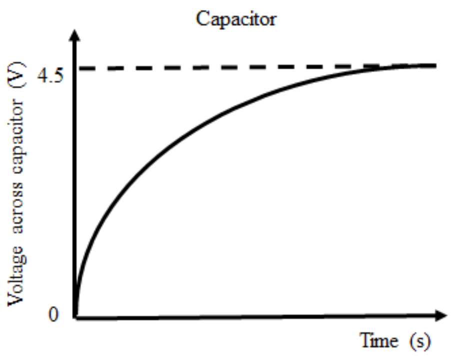
(The resistor is present to set the value of the maximum current which can flow).
Current starts to flow immediately when the switch is closed.

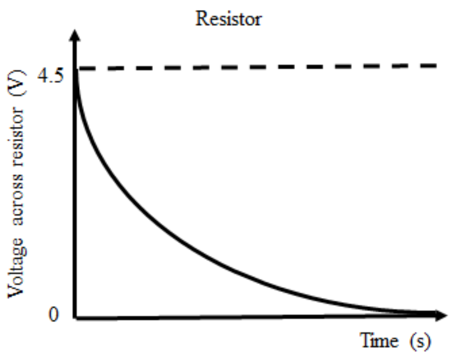
In the circuit, the capacitor and resistor are connected in series. This means that, at any time:

potential difference across capacitor + potential difference across resistor = supply voltage

Voltage time graphs for a charging capacitor

At the instant the switch is closed (time = 0 s), the capacitor is not charged. The potential difference across it is 0.0 V. Therefore the potential difference across the resistor is 4.5 V. As time passes, the potential difference across the capacitor increases. Therefore the potential difference across the resistor decreases. After a certain time, the capacitor will become 'fully charged'. The potential difference across it will be 4.5 V and the potential difference across the resistor equals 0.0V.



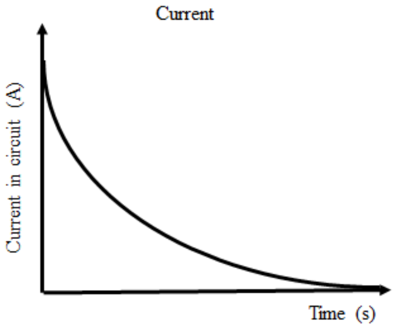


Note that for any particular time, the sum of the voltage across the capacitor and the potential difference across the resistor is equal to the supply potential difference (in this case 4.5 V).

Current-Time Graphs for a Charging Capacitor

The resistor in the circuit sets the value of the maximum current which can flow.

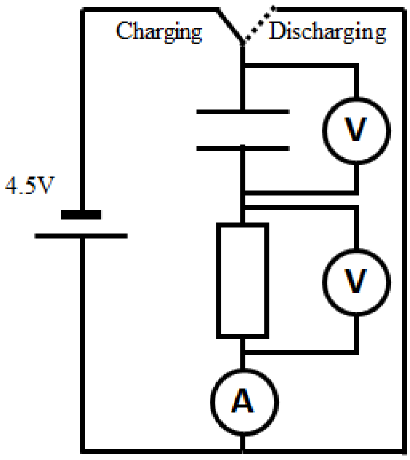
At any instant during the charging process, the size of the current flowing depends on the potential difference across the resistor at that instant and the resistance of the resistor. The capacitor is in series with the resistor, therefore the current flowing through both components will be the same at any particular point in time. A graph of current versus time can be plotted.



The maximum current which can flow is found by calculating V_{supply}/R.

As the capacitor charges, there is greater resistance to flow of charge in the circuit. When the capacitor is fully charged (has a p.d. equal to the supply p.d.) no current can flow.

Graphs for a discharging Capacitor

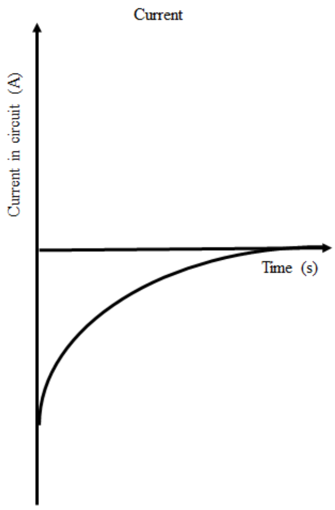


This electric circuit can be used to investigate the discharging of a capacitor. (The resistor is present to set the maximum current which can flow)

Once the capacitor is fully charged, no current is flowing. The capacitor will discharge and the current will start to flow immediately when the switched is moved to the right. Electrons will flow from the bottom capacitor plate, through the resistor and ammeter to the top capacitor plate, until the potential difference across the plates is zero, when no more electrons will flow. The current will be zero.

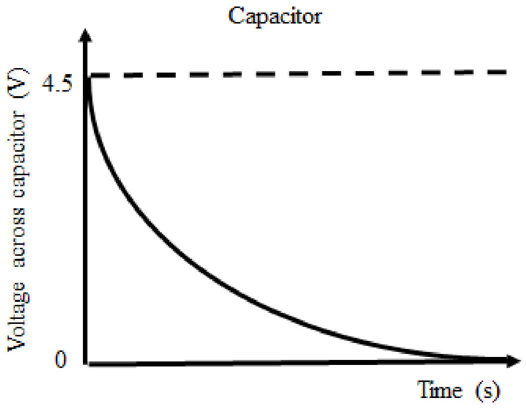
The discharge current decreases from a maximum value to zero.

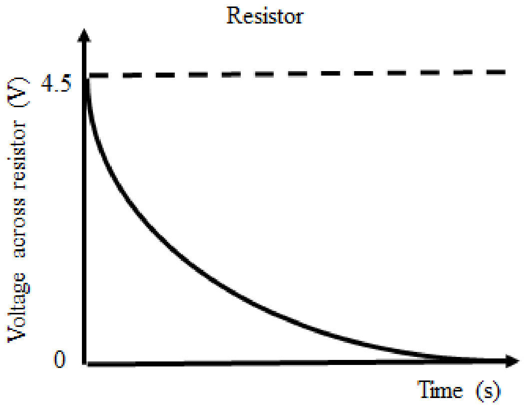
The discharge current is in the opposite direction to the charging current, so it is common to draw the discharging current graph in the form shown here.



The potential difference across the capacitor decreases from the battery voltage to zero.

The potential difference across the resistor decreases from the battery voltage to zero (as the circuit current decreases).





The maximum potential difference across the capacitor always equals the potential difference across the resistor.

Time for a Capacitor to Charge and Discharge

The time taken for a capacitor to charge or discharge depends on the capacitance of the capacitor and the resistance of the resistor connected in series with it.

Increasing the capacitance, increases the charging and discharging time because more charge is stored on the capacitor.

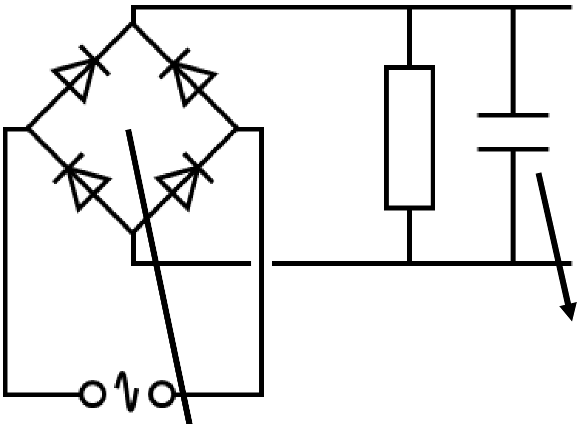
Increasing the resistance, increases the charging and discharging time because a smaller current flows at the start of the process.

Uses of Capacitors

Storing Energy

A camera flash requires a rapid release of energy, this cannot be achieved from a battery, however a battery can be used to charge a capacitor, this capacitor can then provide a very high current.

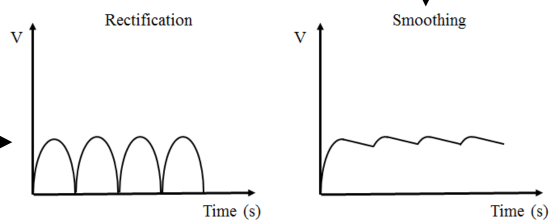
Full wave rectification



Full Wave Rectification is when a number of capacitors are used to smooth a rectified d.c. signal. A rectified d.c. signal is produced when four diodes connected as shown to the left to produce a d.c. output from an a.c. input.

If a capacitor is connected in parallel with the supply, the constant charging and discharging will reduce the rectified voltage to an almost smooth voltage with a small "ripple".

The output voltage is d.c. but it is not smooth. The diode combination produces this output. Such a circuit is known as a Rectifier Bridge.



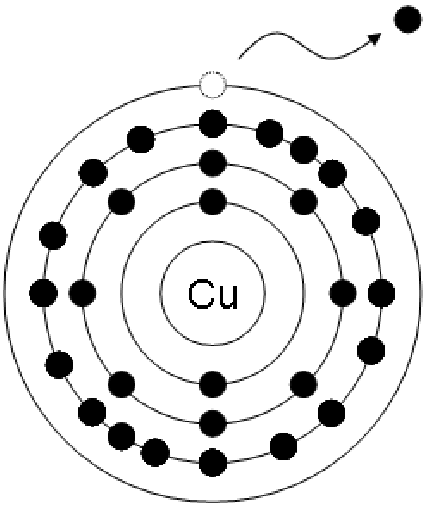
This is how d.c is produced from the mains a.c in the power packs used in the lab.

Energy levels and Energy bands

So far we have met two main types of materials:

Conductors
Materials that allow electrons to move through them - current can flow through them.
Insulators
Materials that do not allow electrons to move - current cannot flow through them.

Example: Copper



- Electrons in atoms are arranged in energy shells
- Each shell can hold a certain number of electrons
- If the shell is full, the electrons are tightly bound to the nucleus
- If the outermost shell is not full, the electrons are not tightly bound and can move away from the nucleus, like the diagram shows.

Conductors	Outer electrons not tightly bound	Examples are metals, semi metals, like carbon-graphite, antimony and arsenic
Insulators	Electrons tightly bound	Examples are plastic, woods and glass.

Band theory

The electrons in isolated atoms occupy discrete energy levels. However, when arranged in the crystal lattice of a solid the electrons in adjacent atoms cannot occupy the same energy levels. Therefore more energy levels come into existence creating bands of permitted energy levels. These bands can be empty, full or partially full of electrons.

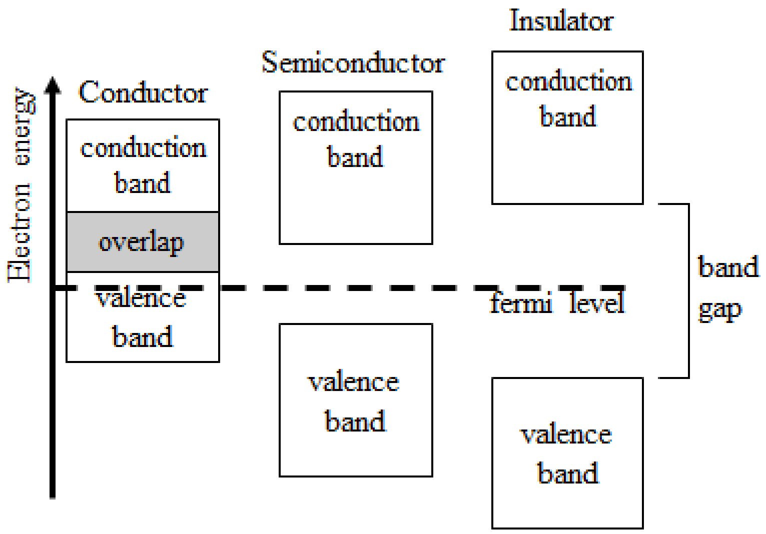
It is important to realize that whenever we talk about conductors, insulators and semiconductors that we are talking about bulk properties of groups of many atoms (this is different to thinking about individual isolated atoms!)

There are two main bands called the valence band and the conduction band. Crucial to conduction is whether or not there are electrons in the conduction band.

	Valence band	Conduction band
Conductors	In a conductor the valence band overlaps the conduction band.	In a conductor, the highest occupied band is not completely full. This allows the electrons to move through the material and conduct easily. This band is called the conduction band.
Insulators	In an insulator the highest occupied band is full. This is called the valence band, by analogy with the valence electrons of an individual atom. Since it is full, electrons cannot move through this level.	The first unfilled band above the valence band is the conduction band. Since it is empty there are no electrons to move through this level.

Conductors, Semiconductors and Insulators

Semiconductors are a third type of solid, with electrical properties in between that of a conductor and an insulator. They behave like insulators when pure but will conduct on the addition of an impurity and / or in response to a stimulus such as light, heat or a potential difference. Band theory helps us understand their electrical properties. Silicon and germanium are examples of semiconductors.



Things to note:
There are groups of energies that are not allowed, creating a band gap. Just as the electrons in individual atoms fill the lower energy levels first; the electrons in a solid will fill the lower bands first. Remember, **the highest fully occupied band in an atom is called the valence band.**

FOR INTEREST: The fermi level

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

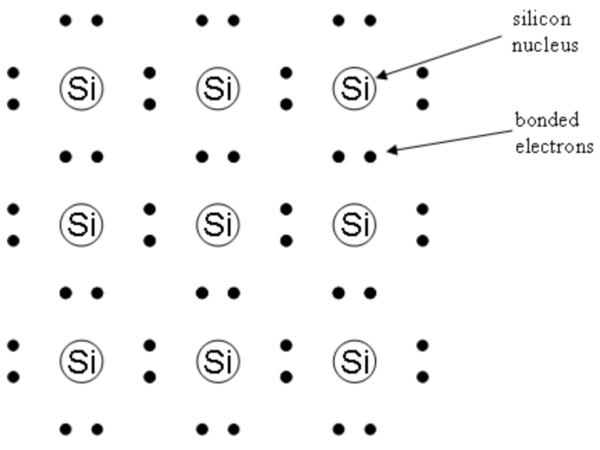
The Fermi level is the maximum permitted energy an electron in a specific structure can possibly have at a temperature of absolute zero (0 kelvins = -273 °C). At room temperature, it is possible for electrons to have higher energies. Thus changes in structure can change the fermi level.

Conductors	The valence electrons are essentially free, depicted as an overlap of the valence band and the conduction band, so that a fraction of the valence electrons can move through the material.
Semiconductors	The gap between the valence band and the conduction band is smaller, and at room temperature there is sufficient energy available to move some electrons from the valence band into the conduction band, allowing some conduction to take place. An increase in temperature increases the conductivity of a semiconductor as more electrons have enough energy to make the jump to the conduction band. This is the basis of a thermistor where an increase in temperature produces a lower resistance.
Insulators	There is a large forbidden energy gap between the valence band and the energy at which electrons can move freely through the material in the conduction band.

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. This makes the resistance very large. Such pure crystals are known as intrinsic semiconductors.

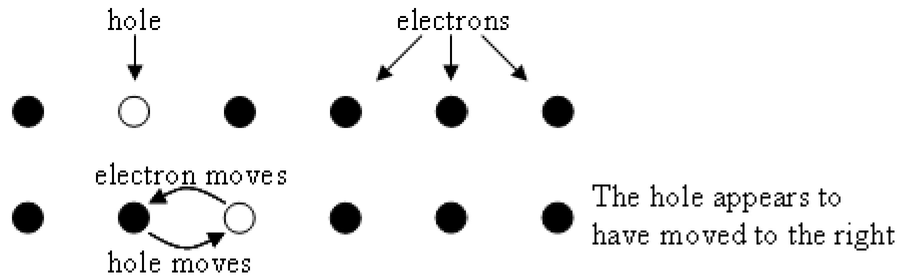


The few electrons that are available come from imperfections in the crystal lattice and thermal ionisation due to heating. A higher temperature will thus result in more free electrons, increasing the conductivity and decreasing the resistance, as in a thermistor.

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 <u>positive hole</u>.

This hole may be filled by an electron from a neighbouring atom, which will in turn leave a hole there. In this model it is technically the electron that moves but 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 a complex semiconductor it is easier to calculate what is happening in terms of one moving positive hole, rather than many electrons.



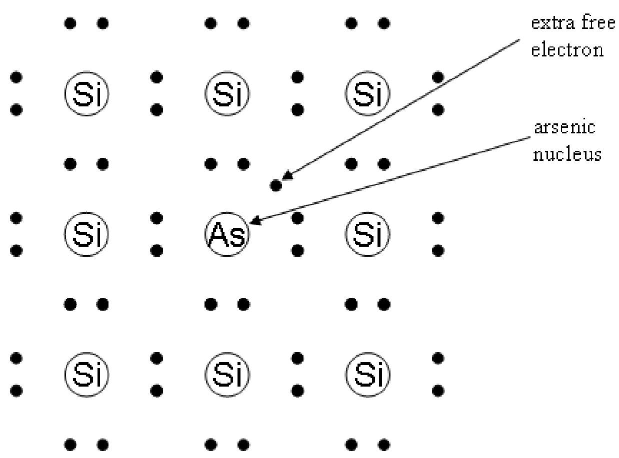
Doping

The electrical properties of semiconductors make them very important in electronic devices like transistors, diodes and light-dependent resistors (LDRs).

In such devices the electrical properties are dramatically changed by the addition of very small amounts of impurities. The process of adding impurities to these semiconductors is known as doping and <u>once doped they are known as extrinsic semiconductors.</u>

<u>n-type semiconductors</u>

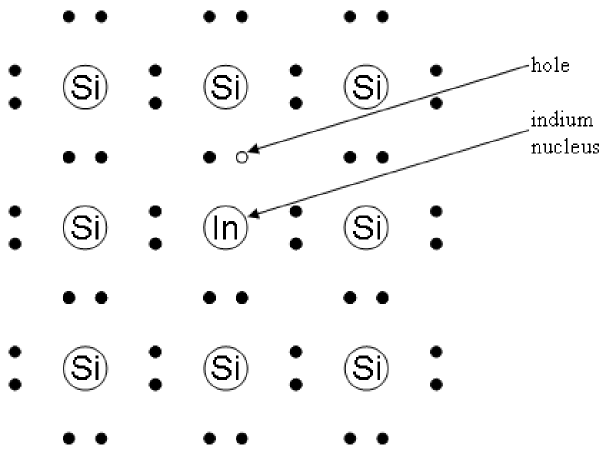
If an impurity such as arsenic (As), which has five outer electrons, is present in the crystal lattice, then four of its electrons will be used in bonding with the silicon. The fifth electron will be effectively free to move about and conduct. Since the ability of the crystal to conduct is increased,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

p-type semiconductors

The 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'. Electrons in the valence band can quite easily move into the energy levels provided by these holes.



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

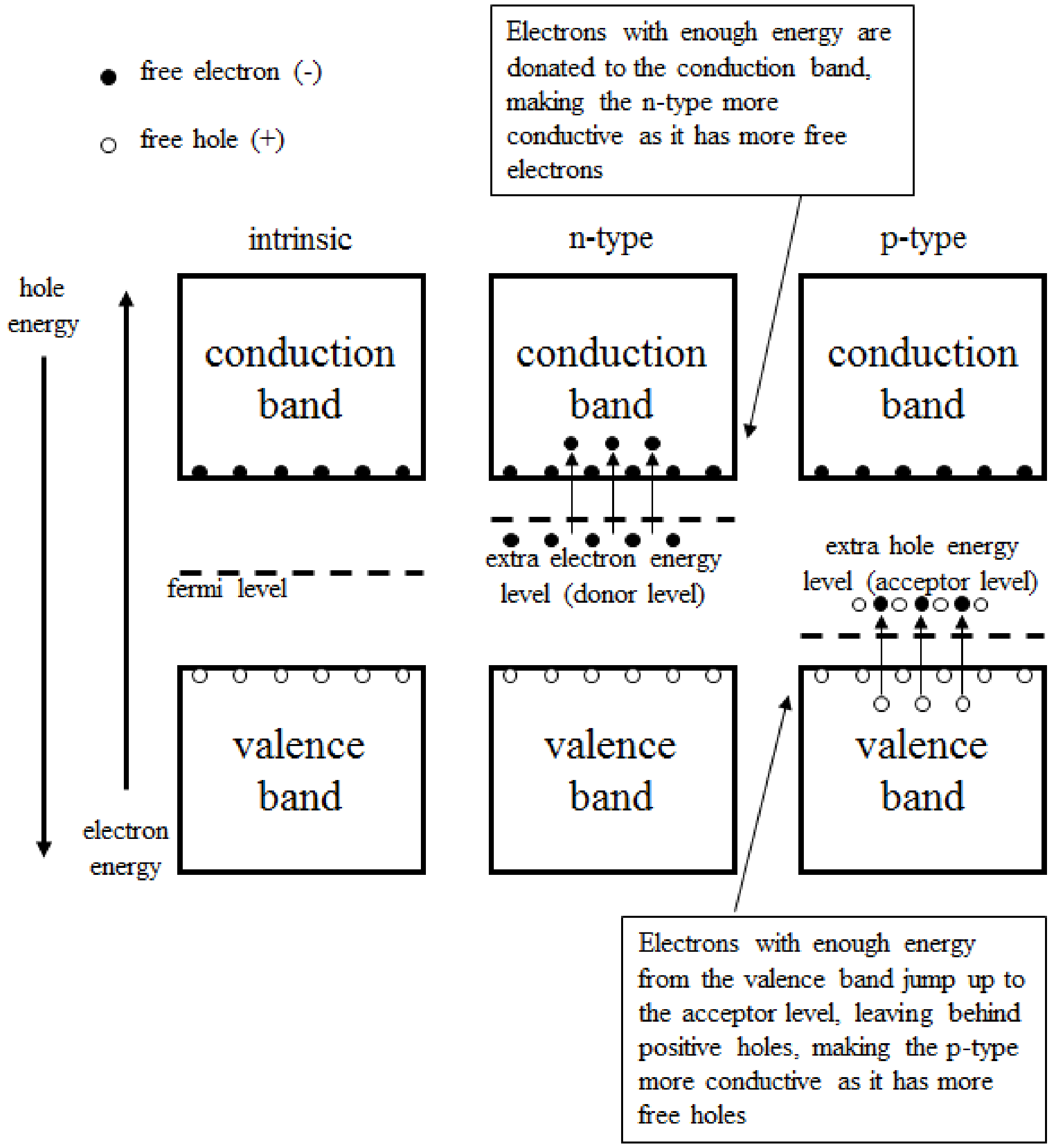
In n-type, the added impurities introduce free electrons to the structure, which exist in an isolated energy level in the band gap (called the donor level), near the conduction band (see diagram on next page).

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 (called the acceptor level), near the valence band (see diagram on next 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.

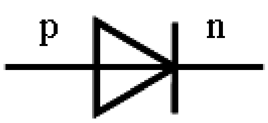


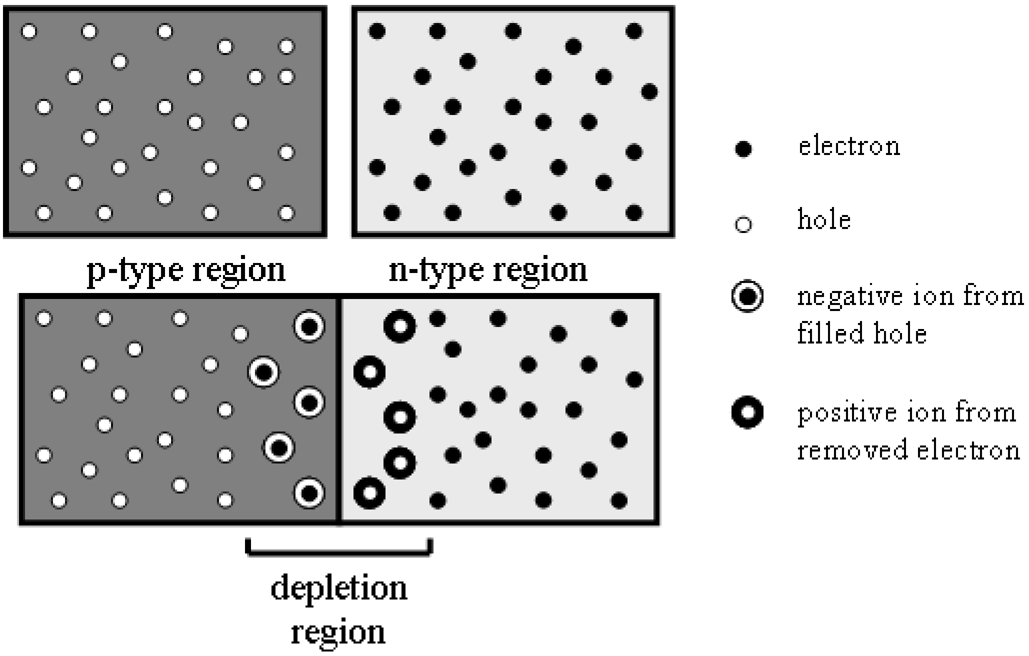
P-N Junctions

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.

At temperatures other than absolute zero, electrons from the n-type material diffuse across the boundary and recombine with holes from the p-type material, and vice versa. This recombination of holes and electrons results in a lack of majority charge carriers in the immediate vicinity of the junction creating a region known as the depletion zone/layer.

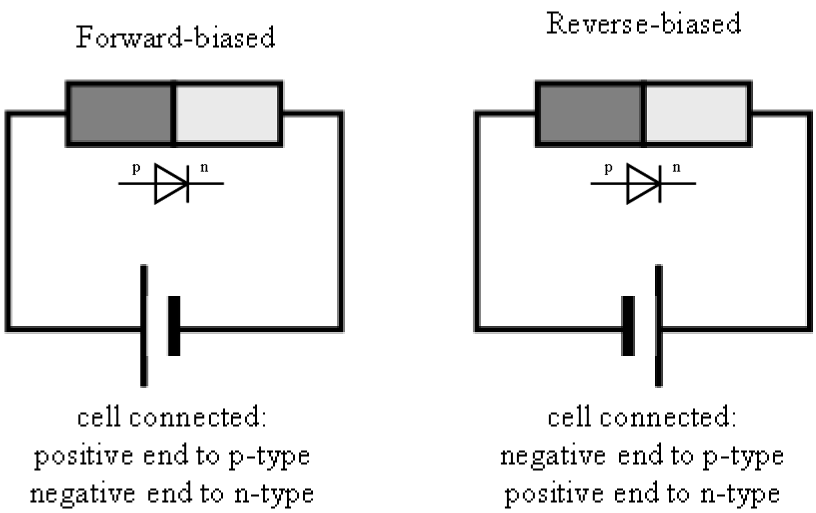
Circuit symbol showing location of p-type and n-type





The biased diode

When we apply an external voltage we say that the diode is biased. There are two possibilities: forward and reverse bias.



<u>Forward Biased</u>

A potential difference of about 0.7 volts exists across the junction of an unbiased diode. To make a diode conduct, a potential difference greater than 0.7 volts must be applied across the diode in the opposite direction.

If the junction is forward biased then the majority charge carriers (electrons in the n-type and holes in the p-type) can flow across the junction and round the circuit. Electrons flow from the n-type to the p-type.

<u>Reverse Biased</u>

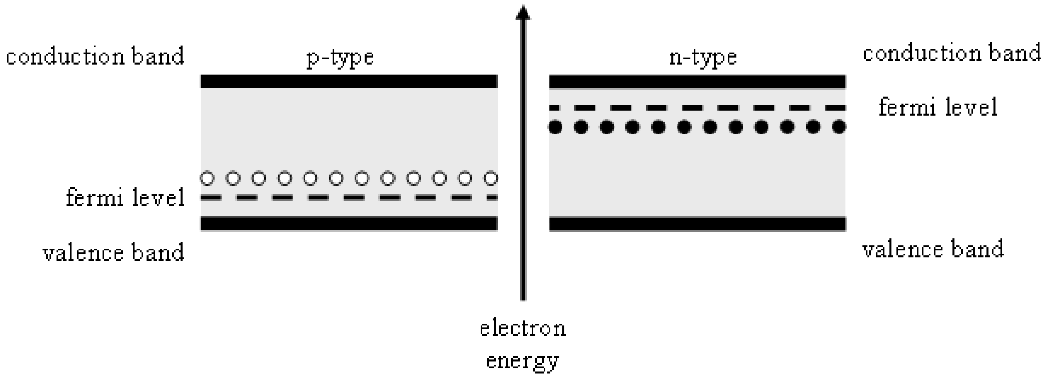
If a potential difference is applied across the diode in the opposite direction we say the junction is reverse biased.

The effect of this reverse potential difference is to increase the width of the depletion layer forming an even greater barrier to the flow of charge carriers. The diode scarcely conducts.

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

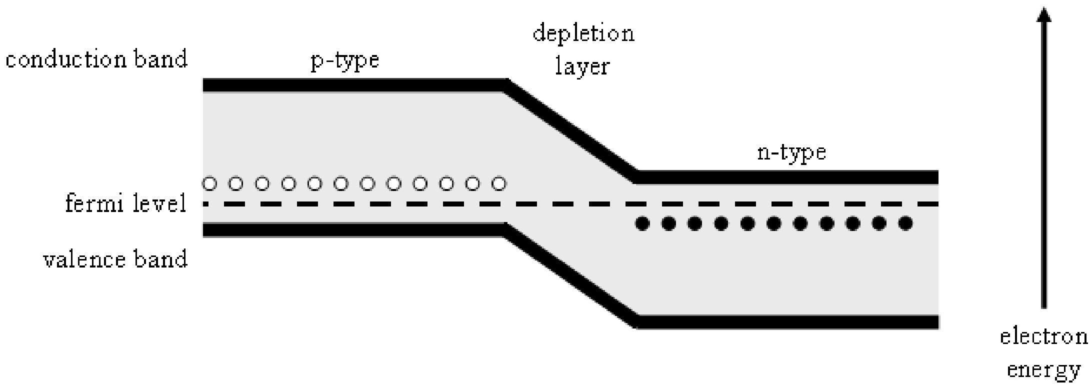
P-N Junctions and band structure

To understand p-n diodes, it is helpful to look at what is happening to the energy bands when the 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 semiconductors the closer they are to the junction.

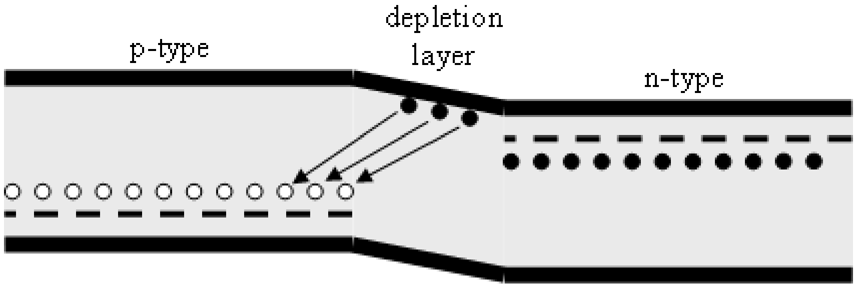
The fermi level is in the middle of the band gap for an intrinsic semiconductor. (See previous band theory diagrams).

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

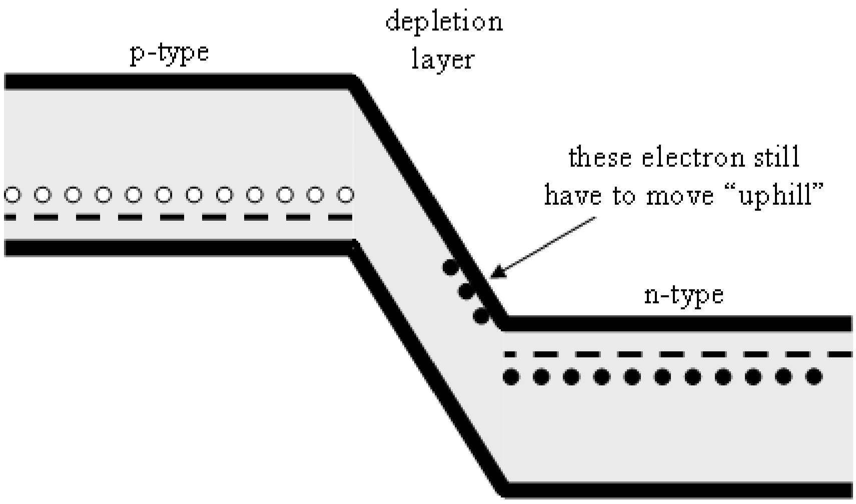
By applying a forward bias (positive voltage) to the diode the difference between the energy bands is reduced, and current can flow more easily. The diode conducts in forward bias. As a result of the bias



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.

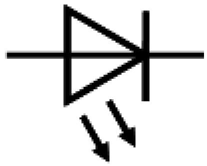
Reverse Biased

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.

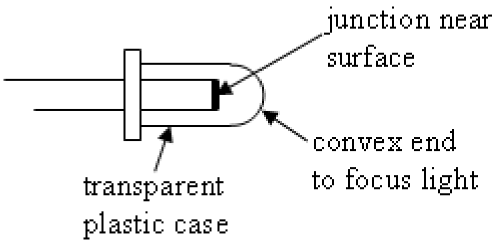


The electrons in the n-type material which have been elevated to the conduction band and which have diffused across the junction are still at a lower energy than the holes in the p-type material. A forward current is not possible.

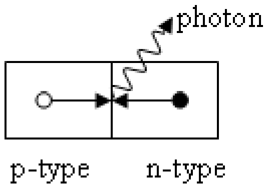
The Light-Emitting Diode (LED)



One example of the use of a p-n junction is in a L.E.D.



In some semiconductors such as gallium arsenide phosphide the energy is emitted as light. If the junction is close to the surface of the material, this light can escape. This is a light emitting diode (LED). The colour of the emitted light (red, yellow, green, blue) depends on the relative quantities of the three constituent materials.



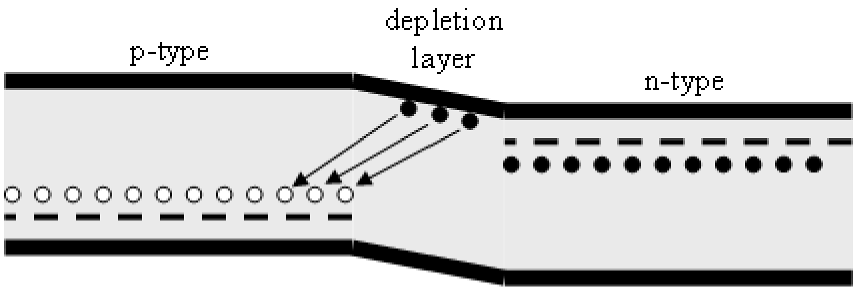
The recombination energy can be calculated if the frequency of the light emitted is measured. The energy is calculated using the formula:

$$E = hf$$

E - is the energy of the photon emitted which is equal to the recombination energy (J)
h - is Planck's constant: 6·63 x 10-34 Js
f - is the frequency of the emitted light in hertz (Hz)

Like other diodes, the LED does not work in reverse bias since the charge carriers do not travel across the junction towards each other so cannot recombine.

LED's and band structure



Holes more to the junction from the positive side →
←Electrons move to the junction from the negative side
Combination of electron and holes occurs near the junction

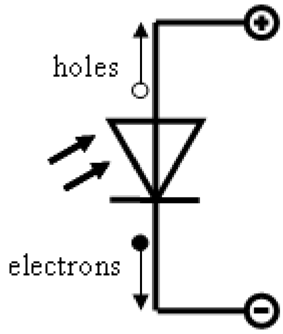
When electrons from the n-type combine with holes in the p-type at the junction, energy is released in the form of light.	For each recombination of electron and hole, one photon of light is emitted.	Recombination energy E=hf Energy can be found by knowing frequency of light emitted

The Photodiode

A p–n junction diode with a transparent coating will react to light in what is called the photoelectric effect. This type of diode is called a photodiode and is the basis for a solar cell.

Photovoltaic mode

Photodiodes can be used in a number of modes (i.e. the same materials but connected in a different way). Solar cells operate under what is called Photovoltaic mode. In this mode the diode has no bias voltage applied. Each individual photon that is incident on the junction has its energy absorbed producing electron-hole pairs. This results in an excess number of electrons in the n-type and an excess of holes in the p-type producing a potential difference across the photodiode.



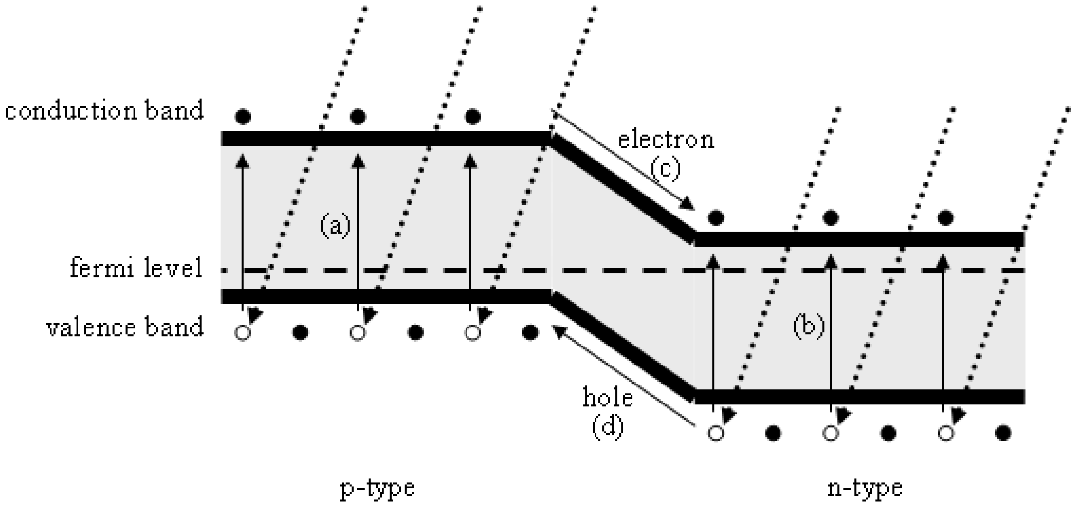
Light has supplied energy to the circuit producing an emf that can be used to supply power to other devices. More intense light (more photons) will lead to more electron-hole pairs being produced and therefore a higher voltage. In fact the voltage is proportional to the light irradiance.

Photodiodes working in photovoltaic mode are:

- usually referred to as photocells
- form the basis of the solar cells used to supply electrical power in satellites and calculators.
- limited to very low power applications (as listed above)
- a photodiode in this mode acts like an LED in reverse

Band structure for photovoltaic mode

Each individual photon incident on the junction has its energy absorbed, and produces **electron-hole pairs**.



(a) p-type - electron moves up to conduction band.

(b) n-type - holes are created in valence band.

(c) electrons move down depletion layer
(P-TYPE = EXCESS HOLES)

(d) holes move up depletion layer
(N-TYPE = EXCESS ELECTRONS)

Potential difference created (emf)