Section IV

Semiconductors and Diodes

(i) Semiconductors

Semiconductors

A semiconductor is a material which, on application of an emf, facilitates a ‘moderate’ current flow.

Semiconductors are a class of materials which fall between conductors and dielectrics. Examples include Silicon (Si) and Germanium (Ge).

As opposed to conductors, where approx. 1 electron per atom is available for conduction, in semiconductors, this figure is typically of the order of 1 electron in every 10^8 atoms.

Example

Consider Silicon (Si), a common semiconductor. 28.1g of Silicon contains 6.02×10^{23} atoms. The density of Silicon is $2.33 g/cm^3$.

So $1 cm^3$ of Silicon contains 5×10^{22} atoms.

Therefore there are approximately $5 \times 10^{12}\ e^-/cm^3$ available for conduction in Silicon at room temperature.

Silicon is a metalloid. Over 90% of the Earth's crust is composed of silicate (compounds of silicon) minerals, making silicon the second most abundant element in the Earth's crust (about 28% by mass) after oxygen.

Holes

When an emf is applied across a semiconductor, the ‘free’ electrons move towards the anode. The ‘space’ left behind, referred to as a ‘hole’, is filled by another electron coming from a neighbouring atom (on its way to the anode).

This ‘hole’ has a small positive charge (because an electron has vacated the outer orbit).

The electron in turn moves further towards the anode and a hole appears in its place until it, in turn, is replenished by another electron coming from the cathode. i.e. the process of charge flow, a.k.a. current, can be viewed as electrons flowing from the cathode to the anode or ‘holes’ moving from the anode to the cathode.

This latter concept is used in semiconductor physics to succinctly explain electrical current phenomena in semiconductor devices.

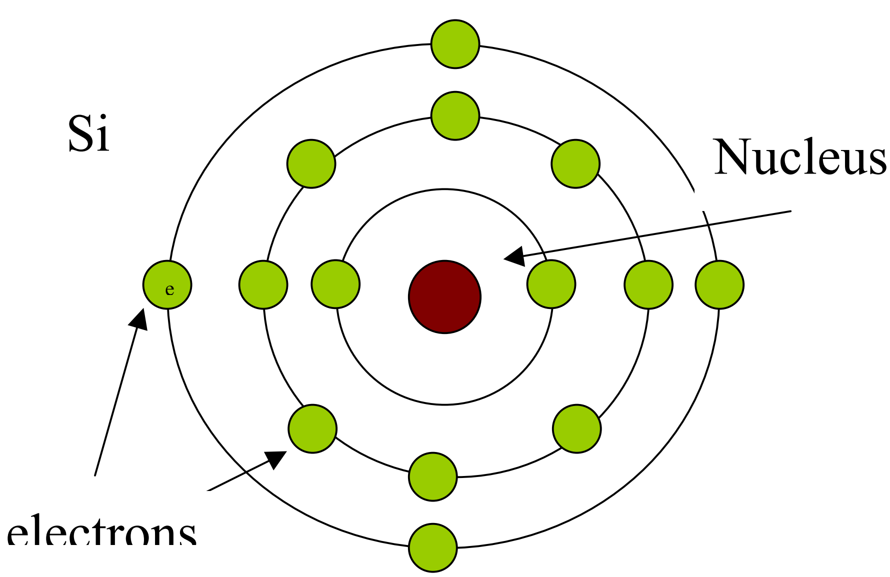
In a pure or ‘intrinsic’ semiconductor, there are the same number of holes as free electrons.

Semiconductor Doping

A process known as ‘doping’, which is the addition of an ‘impurity’ element to an intrinsic semiconductor, is used to enhance the conductivity of the semiconductor itself.

A semiconductor that has been doped is referred to as an ‘extrinsic’ semiconductor.

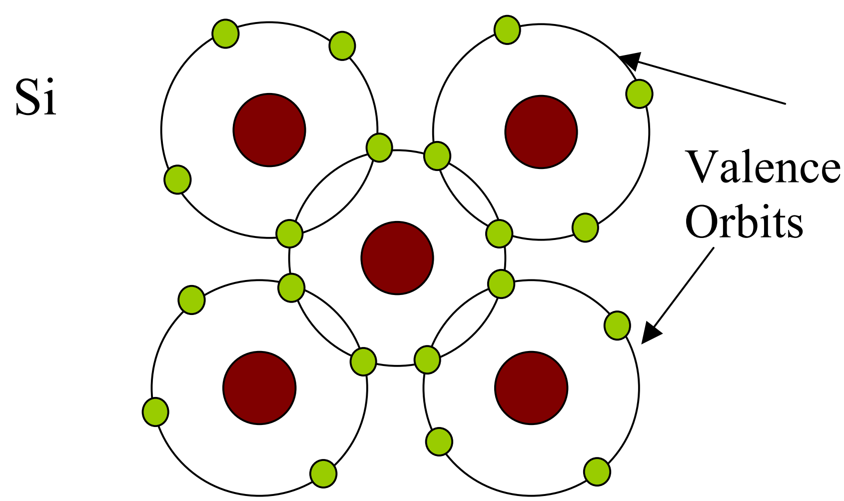
Consider the silicon atom (Si). It has 14 electrons. It looks like this:



i.e. there are four electrons in its valence orbit.

All atoms have a propensity to seek either the full compliment of electrons in their outer-most shell ($2n^2$) or, failing this, eight electrons in the outer-most shell for $n \geq 2$. (Hence, the reason for chemical bonding where atoms share electrons in their outer-most shells.)

Pure silicon achieves the latter in the following manner:



Here the centre atom achieves eight electrons in its valence orbit by sharing its electrons with each of the four Silicon atoms that surround it.

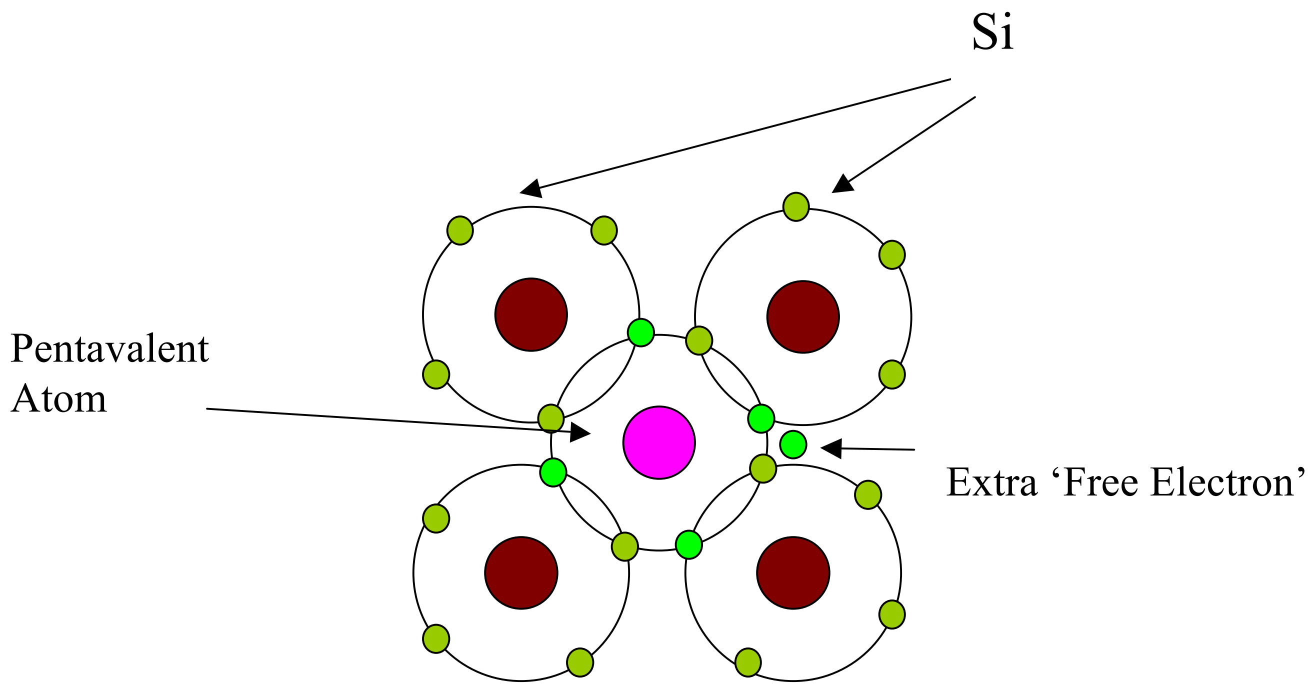
These atoms in turn establish the same relationship with other neighbouring Silicon atoms. It is this regular arrangement that gives Silicon its crystalline structure.

N-Type Semiconductors

These have an enhanced number of free electrons and so have a better conductivity than intrinsic Silicon.

This is achieved by adding pentavalent atoms (i.e. atoms with five electrons in the outer shell) in a process known as ‘doping’. The resulting structure is then:

N-Type Silicon:



Examples of Pentavalent Atoms include:

- Arsenic
- Atimony
- Phosphorus

As we can see the structure is similar to that of pure Silicon but with an electron in the valence orbit ‘left over’. This partially ‘excluded’ electron is a strong candidate for conduction and so an increased presence of such electrons enhances the conductivity of the resulting material.

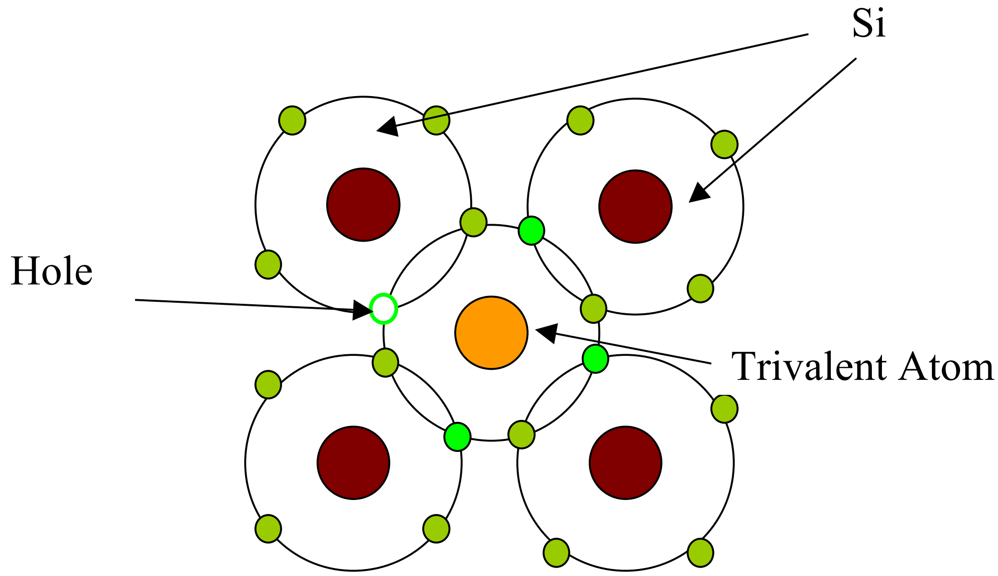
In these materials (n-type semiconductors), there is a greater number of free electrons than there are holes. Hence, we say that the ‘majority carriers’ are electrons.

P-Type Semiconductors

Another way of enhancing the conductivity of an intrinsic semiconductor is to add a trivalent element.

The resulting structure is this:

P-Type Silicon



Examples of Trivalent Atoms Include:

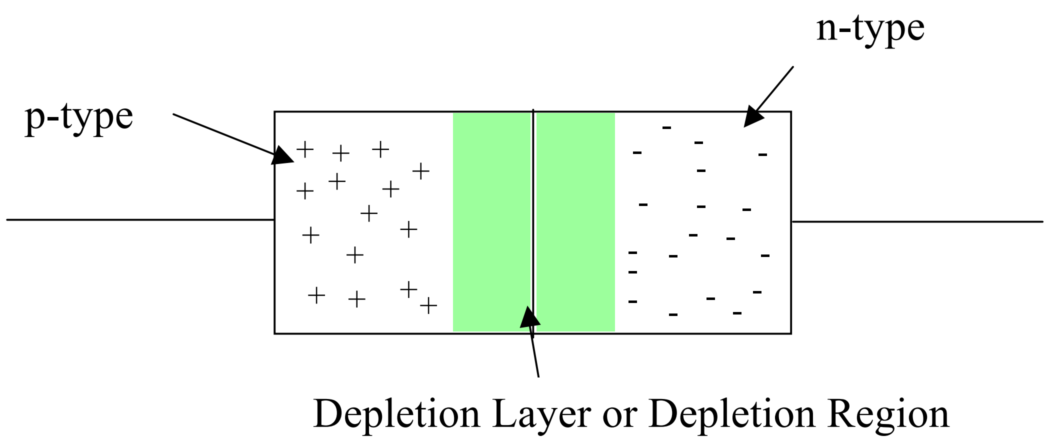
Aluminium
Boron
Gallium

A semiconductor doped with a trivalent impurity element (i.e. an element with three electrons in its valence orbit) is known as a p-type semiconductor. (‘p’ for positive)

The number of ‘holes’ in a p-type semiconductor exceeds the number of free electrons. Hence we say that the ‘majority carriers’ are holes.

(ii) Semiconductor Diodes

It is possible to produce the following crystal:



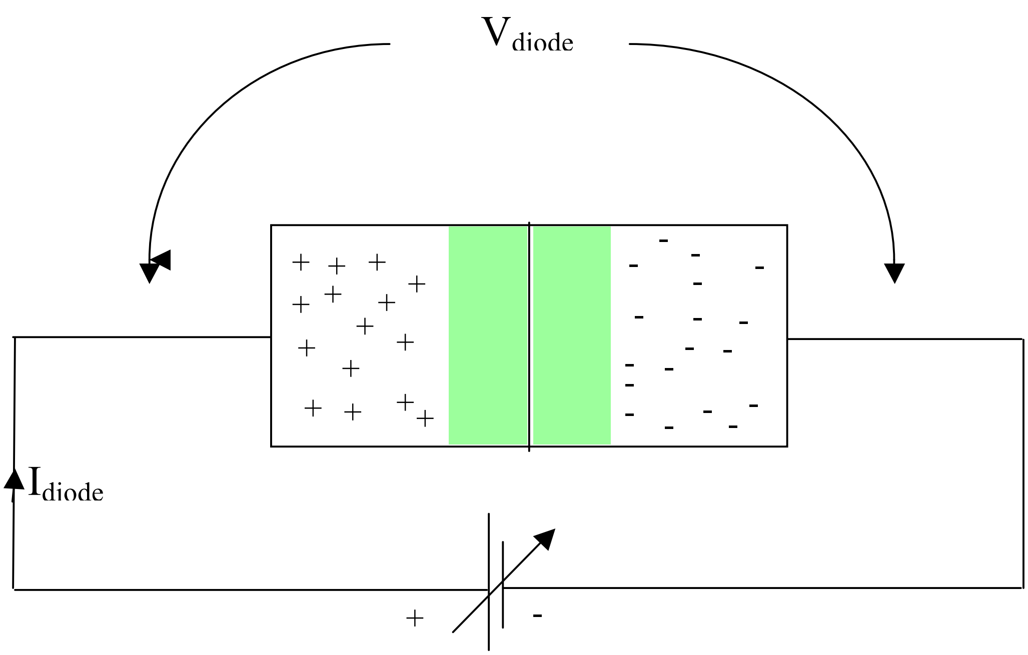
The crystal is composed half of p-type and half of n-type semiconductor material.

The 'depletion layer' at the junction of the p-type and n-type materials is a region devoid of free electrons and holes.

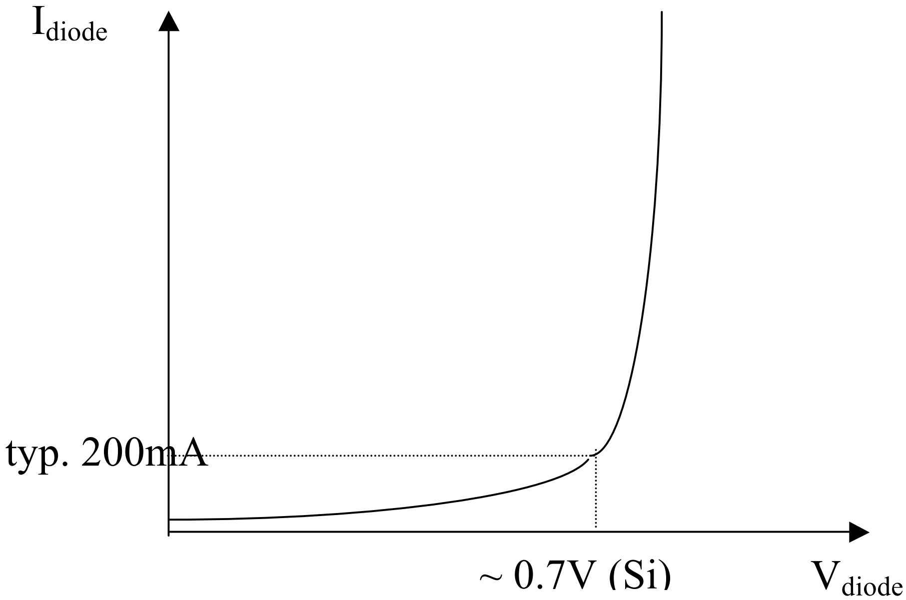
It comes about because free electrons from the n-type material diffuse across the boundary and occupy holes on the other side (and vice versa).

Because the depletion layer has now 'depleted' of charge carriers it becomes a poor conductor of current.

If, however, we apply a variable voltage source as in the following circuit, we notice the following current profile as we increase the emf from zero.



Transfer Characteristic of a Si Diode in Forward Bias:



In this scenario (i.e. the positive terminal of the supply is connected to the p-type material and the negative terminal is connected to the n-type material) the diode is said to be <u>'forward biased'</u>

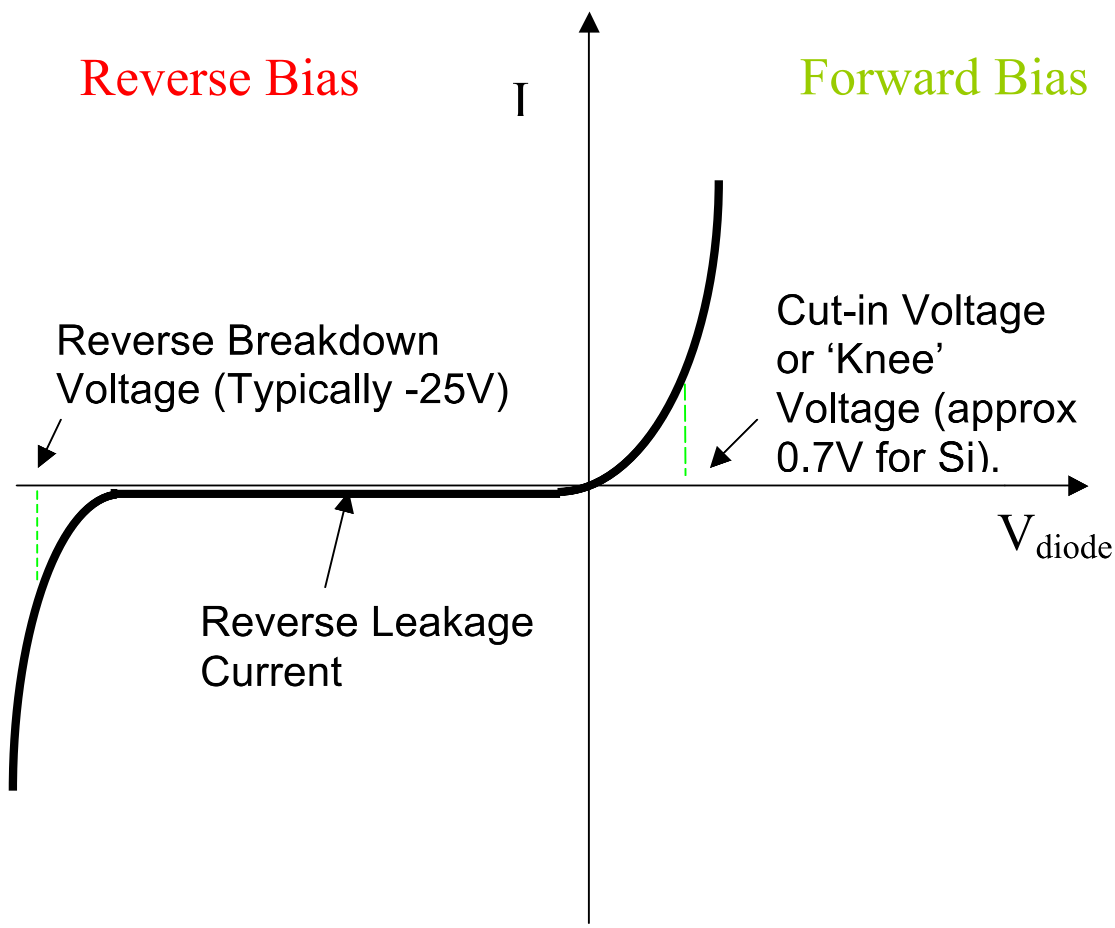
At $V_{diode} \approx$ 0.7 Volts (for a lot of Si diodes), we see an 'exponential' rise in the current.

So, for this diode, at $V_{diode} \approx$ 0.7 Volts, the potential difference (p.d.) between the terminals of the diode is enough to force carriers across the depletion layer – the depletion layer breaks down in the process at which point the crystal is now a reasonably good conductor and current flows freely!

Were one to reverse the polarity of the supply i.e. place the diode in ‘reverse bias’, the depletion region would expand and very little current would flow.

Were one to increase the applied voltage in the reverse ‘direction’ even further, the diode itself would break down. i.e. electrons will simply be forced across the crystal regardless of the fact that it is now entirely a depletion region.

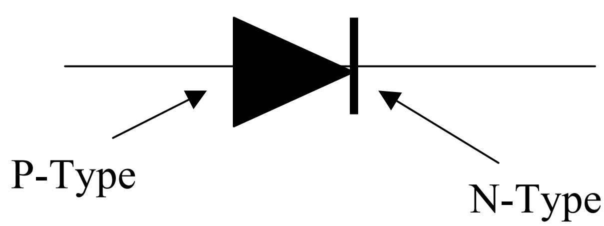
The Full Transfer Characteristic of a Semiconductor Diode (i.e. Forward and Reverse Bias):



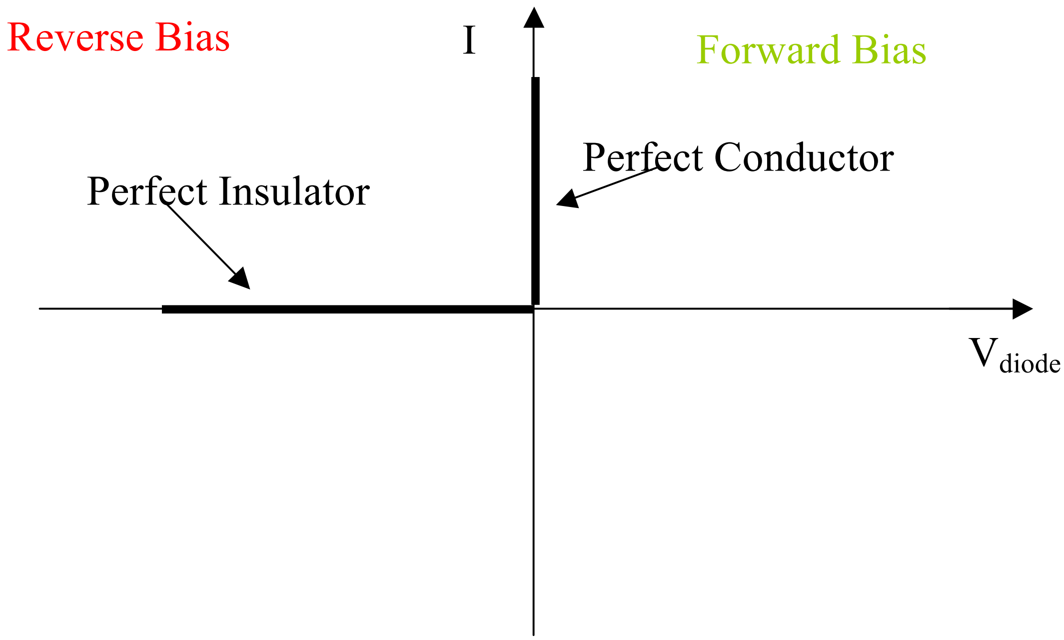
Aside:
The forward characteristic is well approximated by the equation:

$$I = I_o(e^{v/(kT/e^{-1})} - 1))$$

Essentially, the seminconductor diode is a ‘current valve’, allowing current to flow in one direction but not the other.
The electrical symbol of the semiconductor diode is:



The I-V plot of an ‘ideal’ diode would look like this:



The Static Resistance of the Diode

If you take the ratio of the diode voltage to the diode current, you get the ‘Static Resistance’ of the diode (unlike ‘resistors’ diodes do not exhibit a linear relationship between voltage and current)

Example:

In Forward Bias (typical diode IN914):

$$R_s = \frac{0.65V}{10mA} = 65\Omega$$

$$R_s = \frac{0.75V}{30mA} = 25\Omega$$

$$R_s = \frac{0.85V}{50mA} = 17\Omega$$

Note how the resistance decreases as the applied voltage increases.

With the diode in Reverse Bias we get:

$$R_s = \frac{-20V}{25nA} = 800M\Omega$$

$$R_s = \frac{-75V}{5\mu A} = 15M\Omega$$

In both cases, very large resistances.

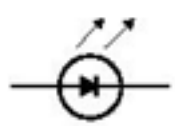
Here are some common specialised diodes:

Zener Diodes

- Designed to operate in the breakdown region
- Symbol: 

A ‘normal’ diode is not designed to operate in the breakdown region. Operation at this point can cause overheating and damage the diode. However if the pn junction is heavily doped the reverse breakdown voltage can be reduced to a point where overheating/damage does not occur (say -5V Vs -25V). Operation at these voltage levels is useful in for example in protecting circuits from voltage surges or in voltage regulators.

Light Emitting Diodes (LEDs)

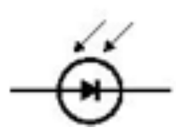
- diodes which emit light on application of a potential difference
- Symbol: 

On application of a potential difference in forward bias electrons combine with holes at the pn junction. In so doing they drop from a higher energy level to a lower one emitting radiation in the process. The frequency of this radiation is determined by the type of semiconductor used. For some semiconductor materials the radiation emitted is visible (i.e. light). Here are some examples:

Typical LED Characteristics			
Semiconductor Material	Wavelength	Colour	V_F @ 20mA
GaAs	850-940nm	Infra-Red	1.2v
GaAsP	630-660nm	Red	1.8v
GaAsP	605-620nm	Amber	2.0v
GaAsP:N	585-595nm	Yellow	2.2v
AlGaP	550-570nm	Green	3.5v
SiC	430-505nm	Blue	3.6v
GaInN	450nm	White	4.0v

Photodiodes

- Diodes which conduct current on application of light

- Symbol: 

The principle of operation of these diodes is the same as that of LEDs but in reverse. When light impinges on the diode it imparts energy or energy is absorbed by the diode. This results in electrons gaining energy and leaving the valence orbits and resulting in the creation of free electron – hole pairs i.e. charge carriers. If a very small voltage is applied these charge carrires move to the anode and cathode respectively. There are thus two currents flowing in the photo diode: the Dark Current which is the current flowing in the absence of light due to the small voltage supply and the photocurrent due to the impact of incident light. The dark current must be minimised to maximise the sensitivity of the device.