XMUT204 Electronic Design

Lecture 2a - Diodes and PN Junctions

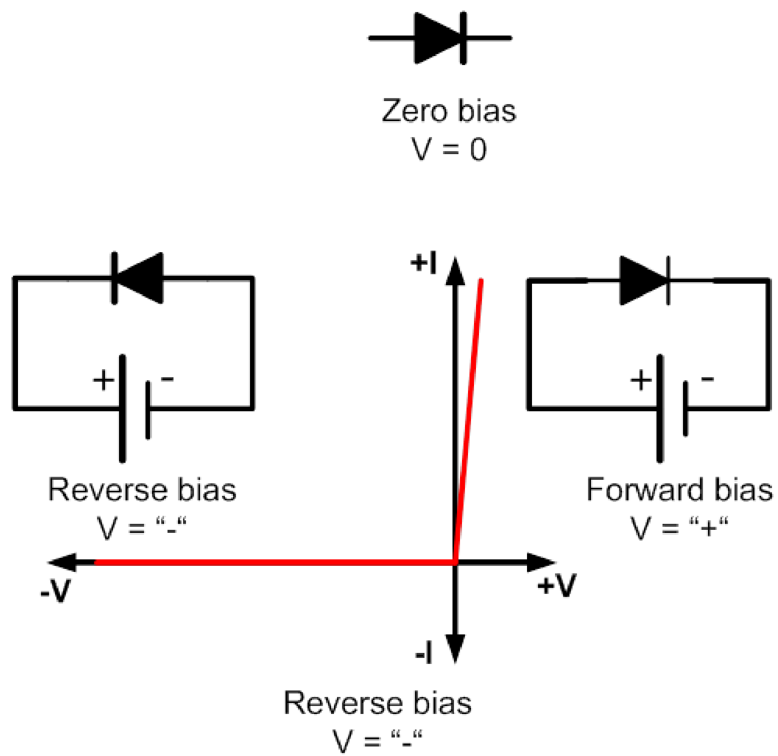
Overview

1. Characteristics of diode.
2. PN junctions.
3. Operations of diode.
4. Current-Voltage characteristics.
5. Applications of diode.

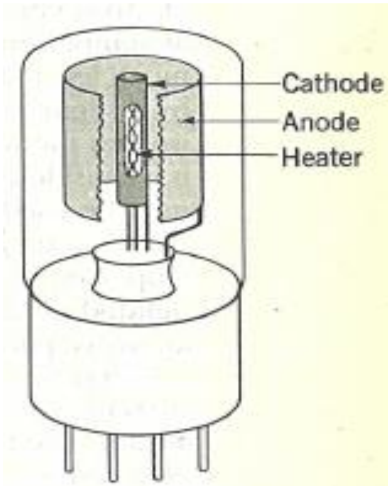
1. Characteristics of Diode

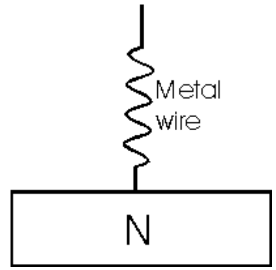
A diode should have a very low resistance to current in the one direction and a very high resistance to current in the opposite direction.

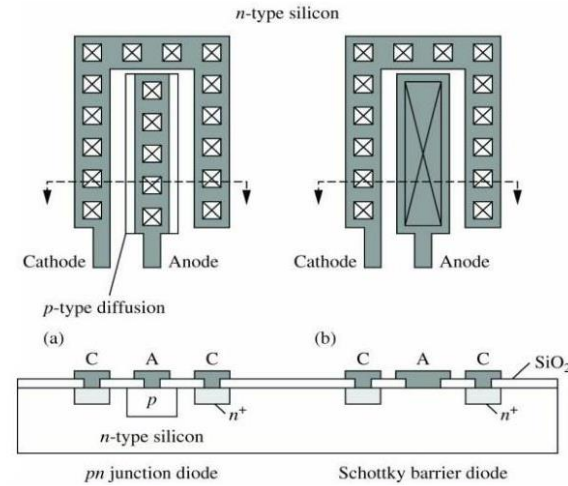
- **Zero biased:** at $V = 0$, no current flows ($I = 0$).
- **Forward biased:** cathode to *negative* source and anode to *positive* source -> very low resistance to current flow and large currents flow for small applied voltage.
- **Reverse biased:** cathode to *positive* source and anode to *negative* source -> very high resistance to current flow and zero/very small currents flow for small applied voltage.

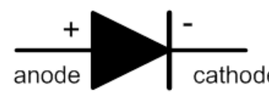


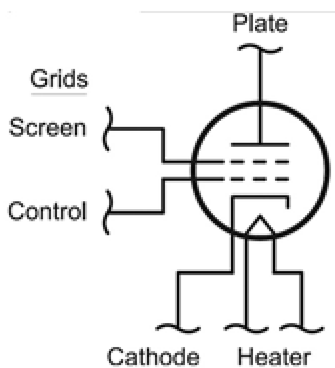
1. Characteristics of Diode (cont.)











Point contact diode

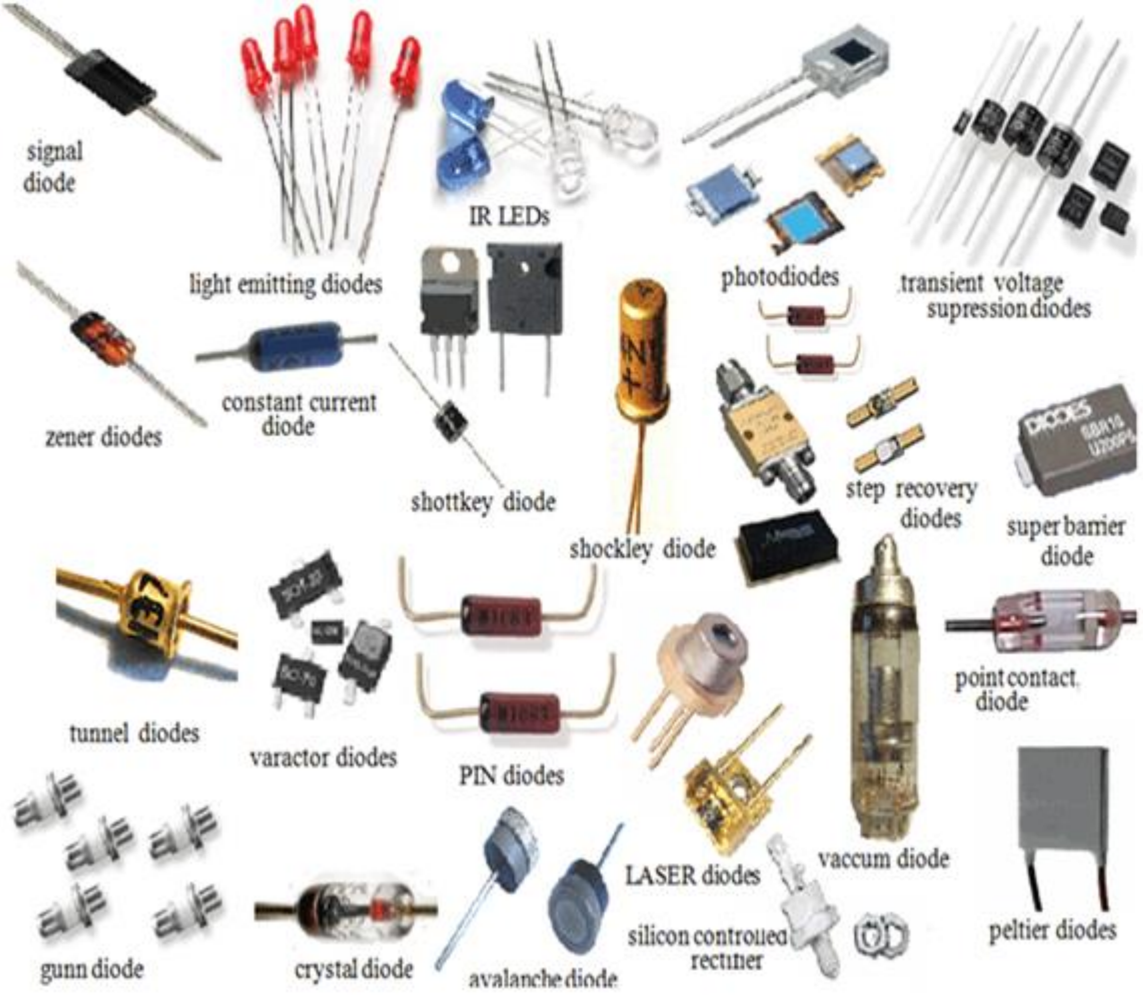
Contemporary diode

Vacuum tube diode

- Electrical valve -> Diode e.g. allows current to flow in only one direction.
- A p-n junction is one type of diode – several other configurations possible.

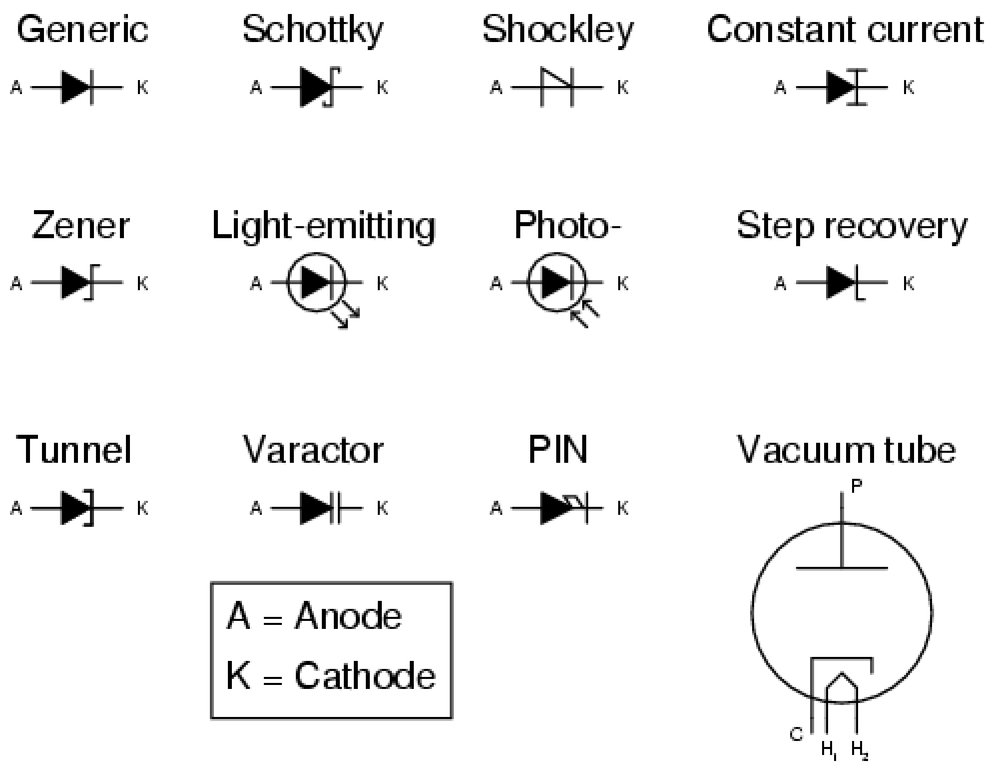
1. Characteristics of Diode (cont.)

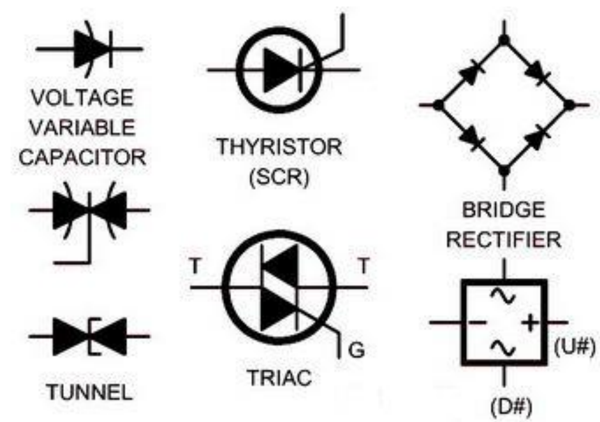
- The following diagram outlines some of the most common types of diodes available in the market.



1. Characteristics of Diode (cont.)

- The following diagrams are symbols of common diodes (left) and extended diode symbols (right)



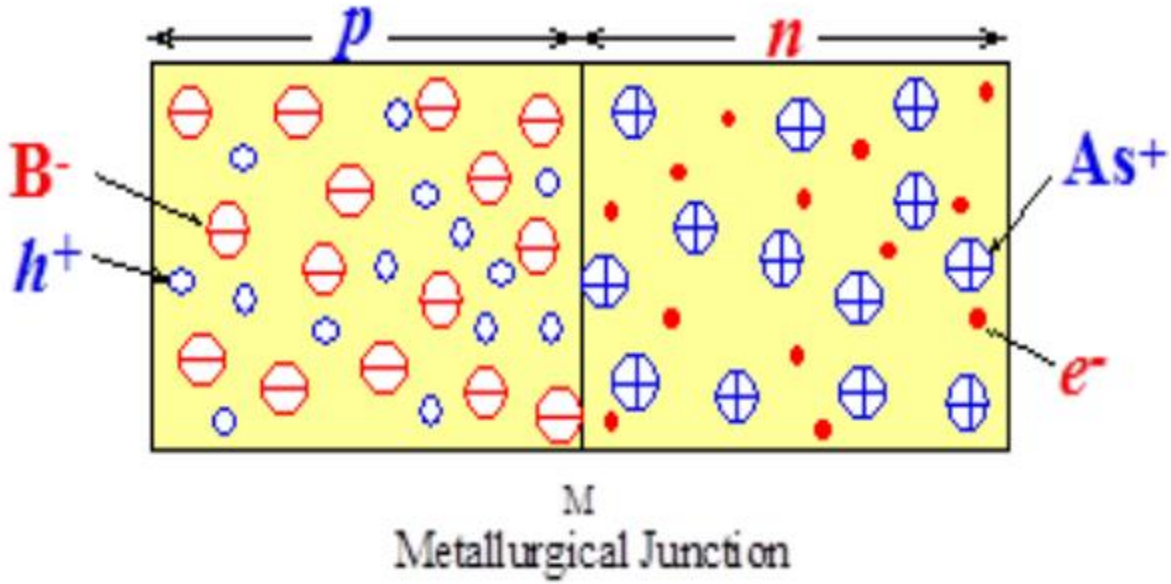


2. PN Junction

The pn junction: Zero bias behaviour

Assume a slab of n-type semiconductor that is brought in contact with a slab of p-type material, forming a **metallurgical junction** as shown in the next slide.

From Section 1: The n-type material will contain a high concentration of free electrons, while the p-type material will contain a high concentration of mobile holes as the majority carriers. A concentration gradient will thus exist for electrons from the n-type (high concentration of electrons) to the p-type material (low concentration) and similarly a concentration gradient will exist for holes from the p-type to the n-type material.



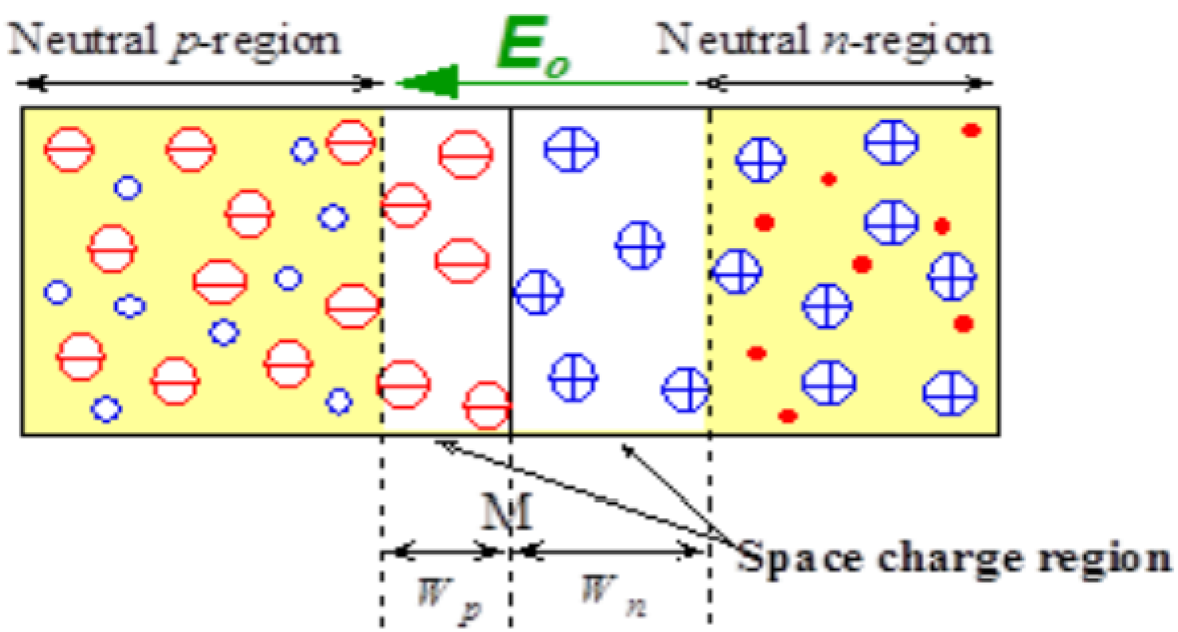
The junction between p-type and n-type semiconductors immediately after joining – no movement of charge carriers has taken place yet.

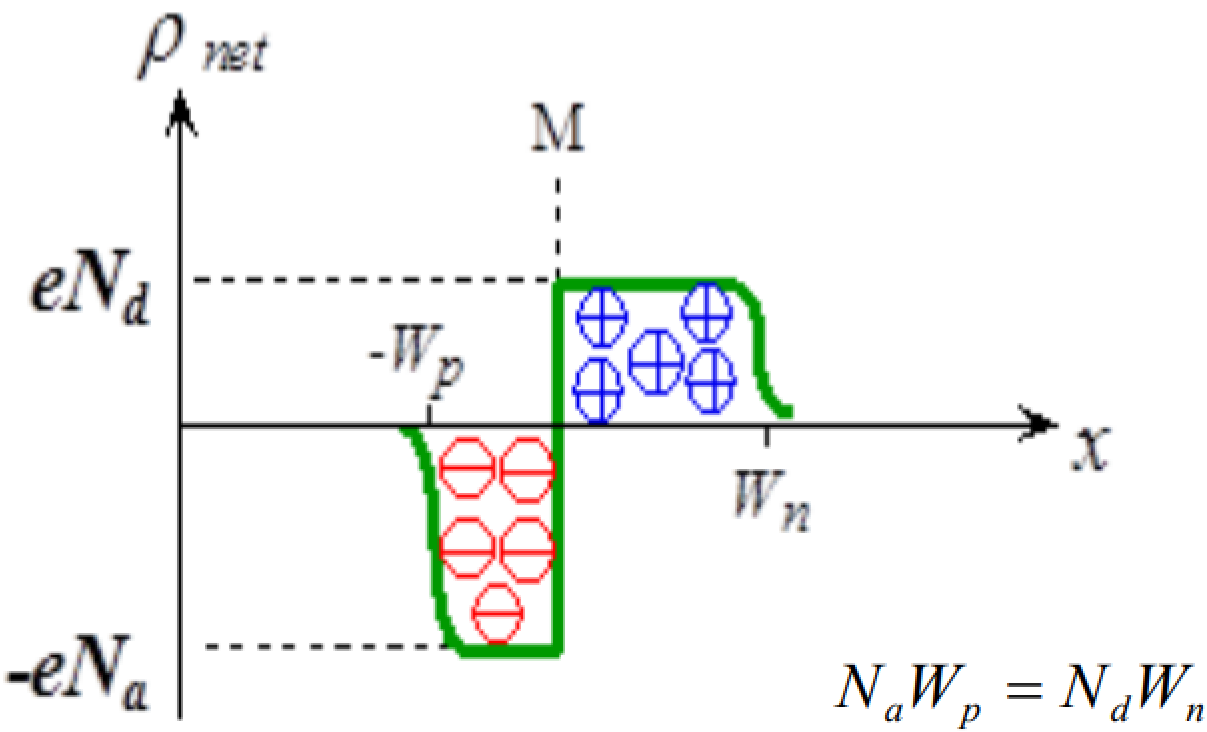
Charge carriers will now start to flow:

The majority carriers on each side will start to flow (diffuse) along the concentration gradients, with electrons flowing into the p-type material and holes flowing into the n-type material. This movement of carriers is called **diffusion current**.

Holes diffusing and entering the n-side will recombine with electrons on that side near the junction, while electrons diffusing into the p-side will recombine with holes near the junction, with the recombination process leading to the removal of these free carriers from the material. The effect of this electron-hole recombination is the formation of a region around the metallurgical junction that becomes depleted of mobile charge carriers – the so-called **depletion layer**.

This region is also called **<u>the space charge layer (SCL)</u>**, as the depletion of carriers in this region will expose the stationary ions that form part of the crystal lattice – negative ions (B^-) on the p-side and positive ions (As^+) on the n-side. A space charge layer thus forms around the metallurgical junction with fixed positive charge on the n-side and fixed negative charge on the p-side.





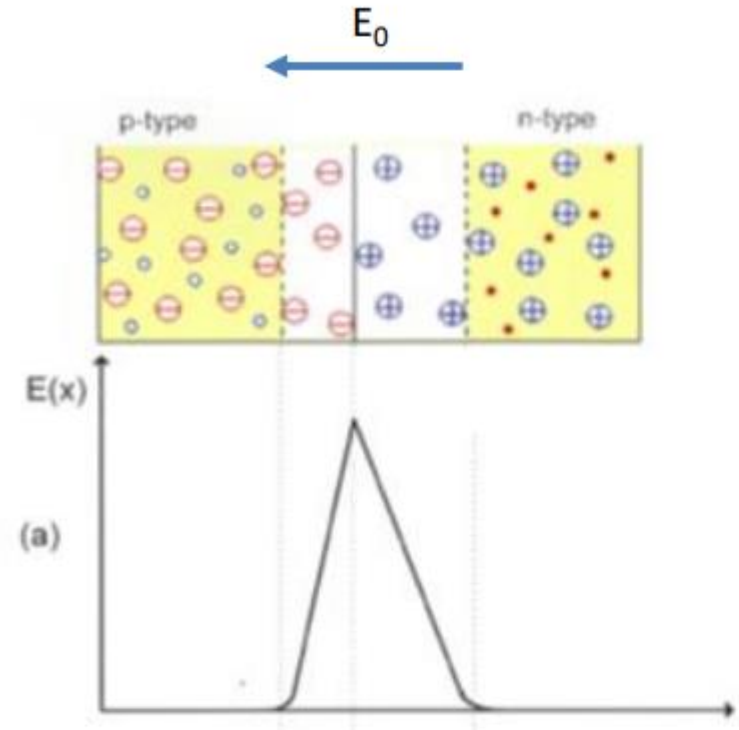
Distribution of immobile charged ions in the space charge layer. Note that the width of the SCL is determined by the doping density in that material.

The space charge layer does not need to be symmetrically around the junction. The width of the space charge layers on each side of the junction is determined by the doping density on that side; a low doping density will lead to a wider space charge layer and a high doping density will lead to narrow space charge region. The total charge on the one side of the junction must equal the total charge on the other side, so that for charge neutrality to hold we must have:

$$N_a W_p = N_d W_n$$

where N_a is the acceptor (p-type) doping level, W_p is the depletion width on the p side, N_d is the donor (n-type) doping level and W_n is the depletion width on the n side.

Due to the SCL we will then have an internal electric field across the junction; the direction of this field will be from the positive ions on the n-side to the negative ions on the p-side.(Direction of the electric field is defined as the direction of a positive charge carrier).



The direction of this field will then oppose the movement of charge carriers due to diffusion. As a consequence the flow of majority carriers will then stop when balanced out by the force from the SCL on a carrier.

However, an electron which enters this internal electric field will then experience a force (F = qE) and drift from the p-side to the n-side under the influence of the field, while a hole that enters this field will drift from the n-side to the p-side under influence of the field.

This movement of charge carriers under the influence of the internal electric field is termed the **drift current**. In each case the direction of drift is then opposite to the direction of the diffusion current due to the concentration gradient. The charge carriers in each case are the minority carriers in each type of material.

The result is that an equilibrium situation is reached where the diffusion current for each particle is exactly balanced by the drift current.

Important to note that we will have two types of currents that will flow across a pn junction:

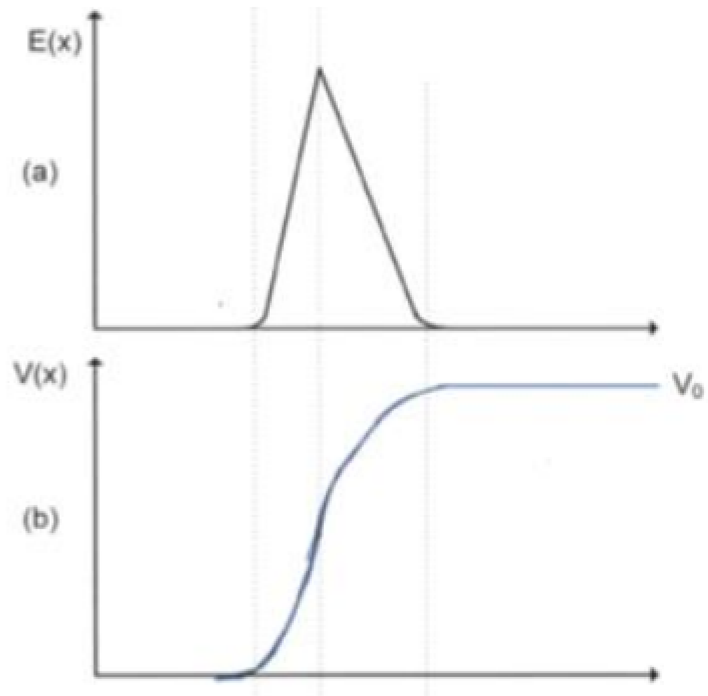
1) The diffusion current made up of majority carriers on both sides and driven by concentration gradients in these carriers

2) The drift current made up of the minority carriers on each side and driven by the built-in electric field across the junction that will sweep available carriers across.

The electric field will not be uniform as for a parallel plate capacitor, but starts at zero at the one edge of the space charge layer, reaches a peak at the metallurgical junction and then declines to zero at the opposite edge of the space charge layer.

Due to the electric field across the SCL we will also have an electrical potential difference (voltage) across this region. The relationship between the voltage (V) and the electric field (E) is given by:

$$E = -\frac{dV}{dx}$$



Thus have a built-in voltage V_o across the junction, with magnitude given by:

$$V_0 = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right) = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

Note that this is **the internal voltage across the junction with no applied voltage**, it is not the voltage that will be measured at the electrodes attached to the semiconductors to form the complete diode.

The term V_T is called the thermal voltage and has a value of ~0.026 V at 300 K.

$$V_0 = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right) = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

It is clear that the value of this built-in voltage will depend on several factors:

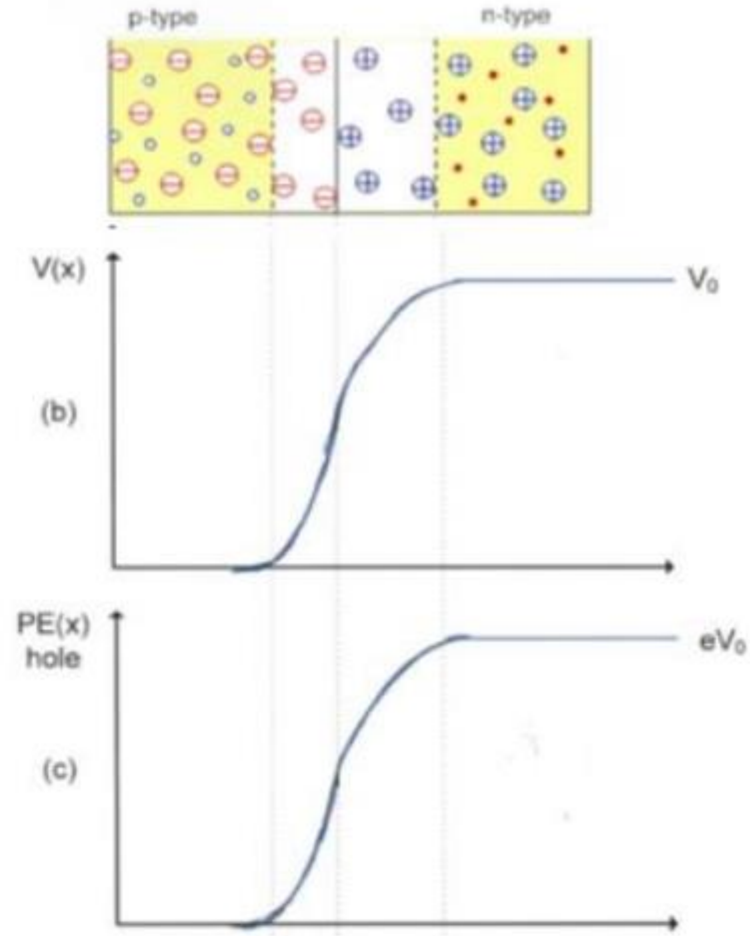
- The doping levels N_a and N_d
- The value of n_i (squared) which will of course be determined exponentially by the temperature and the value of the energy gap in the material.

We can then expect V_0 to be strongly influenced by temperature variations.

Due to the built-in potential difference, a charged particle will have a variation in potential energy across the junction, given by:

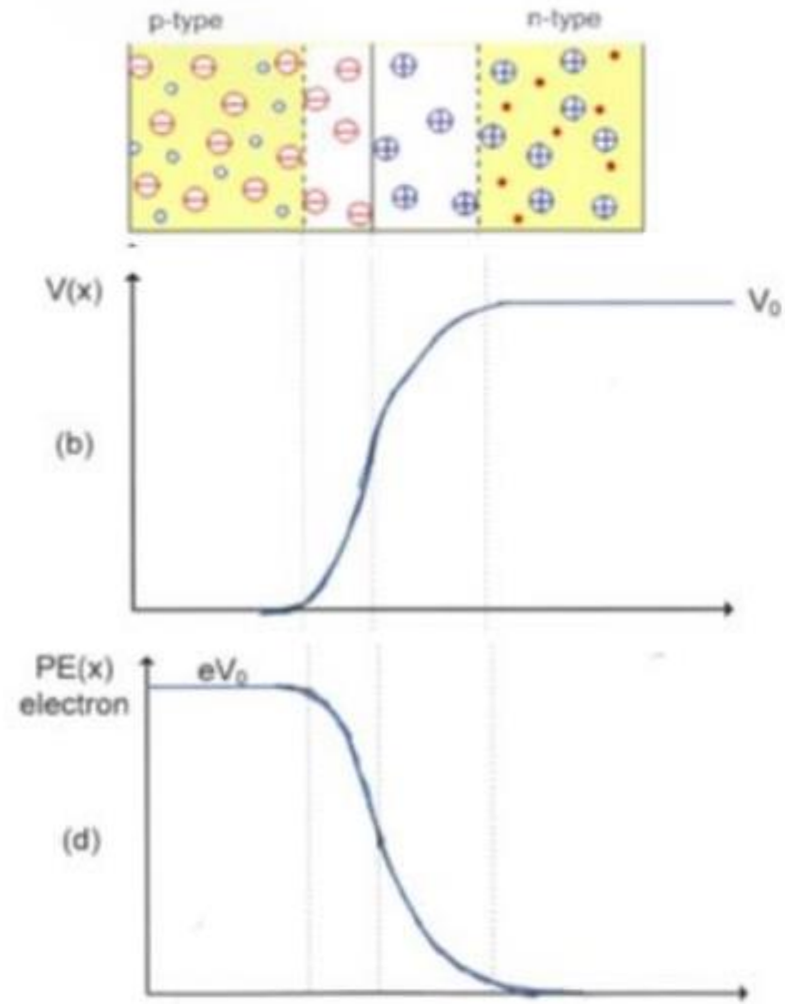
$$PE(x) = eV$$

For a hole we get the curve as shown at bottom right - a hole in p-type material will be at low potential energy and by moving it into the n-type material we will have to raise its potential energy. There is then a potential energy hill for holes in p-type to move to n-type.



As expected, we get inverted curves for electrons and holes – an electron in n-type material will be at a relatively low potential energy, moving it to the p-type material raises the potential energy.

The potential energy curve for electrons is then simply the reverse of that for holes and there is a potential energy hill for electrons in n-type to move to p-type.



In summary, at equilibrium in the unbiased p-n junction no net current will flow. Any diffusion current of majority carriers (holes from p-side to n-side or electrons from n-side to p-side) will be balanced by a drift current of minority carriers (holes from the n-side to the p-side and electrons from the p-side to the n-side).

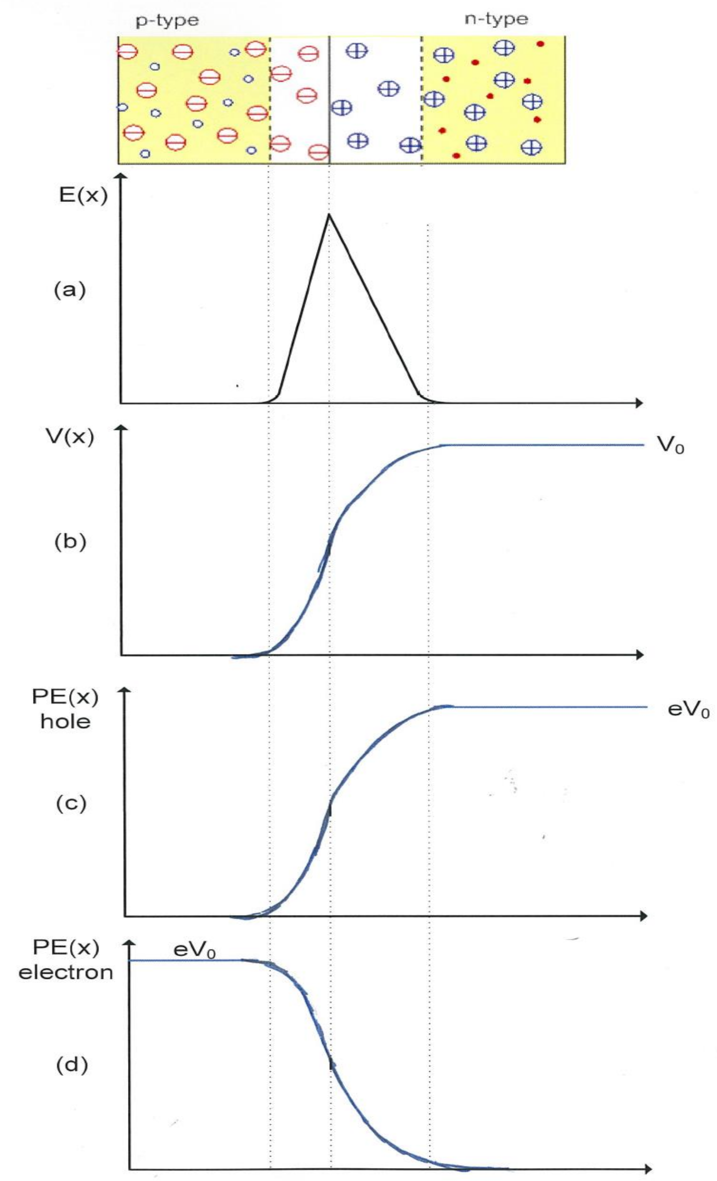
In the absence of an applied bias voltage the net flow of charge in any one direction across the semiconductor junction will thus be zero.

Example for Tutorial 1:

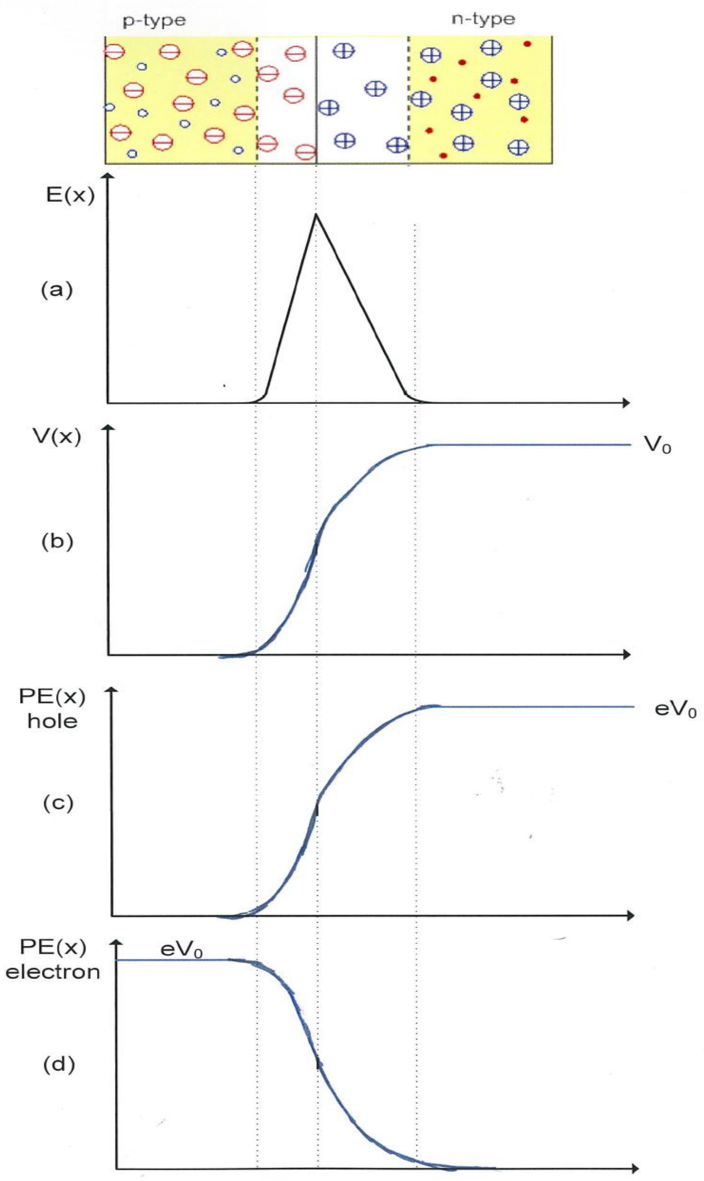
When the n-type semiconductor is joined with the p-type semiconductor, a PN junction is formed. Describe briefly how the potential energies are formed in the PN junction.

[2.5 marks]

- Due to the space charge layer, there is internal electric field across the junction.
- Direction of the field is from the positive ions on the n-side to the negative ions on the p-side.
- Direction of this field opposes the movement of charge carriers due to diffusion.



- An electron inside internal electric field experience a force ($F = qE$) and drift from p-to n-side under the influence of the field.
- A hole in this field will drift from the n-to the p-side under influence of the field.
- Potential energies are formed due to electrons concentration in the n-side and holes concentration in the p-side respectively.
- See the PE diagrams for hole and electron concentrations.



Example for Tutorial 2:

Given that the intrinsic carrier density of Si is 1×10^{10} cm^{-3}, determine the built-in potential in the PN junction (e.g. p-doping level is 1.5×10^{15} cm^{-3} and n-doping level is 7.5×10^{16} cm^{-3}). [2.5 marks]

- The built-in potential in the diode junction is found from the following equation:

$$V_0 = V_T \,\mathrm{Ln}\left[\frac{N_A N_B}{(n_i)^2}\right]$$

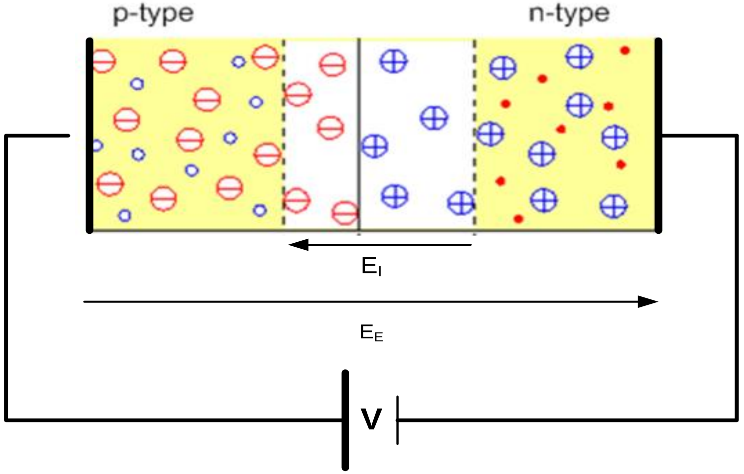
- Putting in the values into the equation:

$$V_0 = 0.025 \times \mathrm{Ln}\left[\frac{(7.5 \times 10^{16})(1.5 \times 10^{15})}{(1 \times 10^{10})^2}\right]$$

$$= \; 0.025 \times \mathrm{Ln}\,(11.25 \times 10^{11}\,) = 0.694\ \mathrm{V}$$

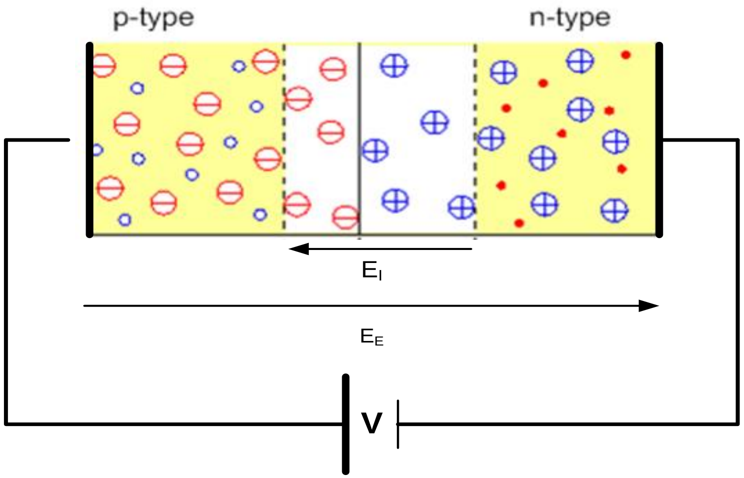
3. Operation of Diode (Forward Bias)

- For forward bias condition, there are 3 regions: p-type bulk material, depletion or space-charge layer, & bulk n-type region.
- Bulk regions have reasonable conductivities, but depletion region has a very low conductivity (high resistance, no free charge carriers in this region).
- Due to this high resistance -> voltage drop (V) appears over the space-charge layer.

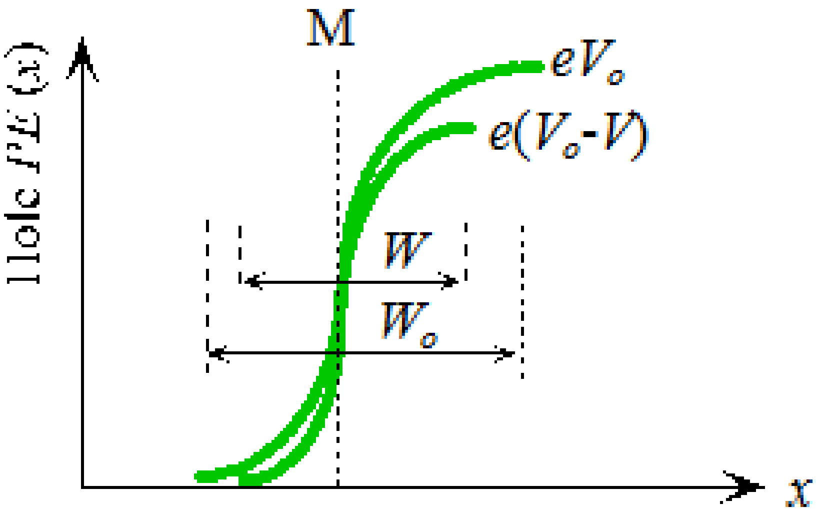


3. Operation of Diode (Forward Bias)

- For forward bias condition, increase in holes that diffuse from p-side to enter n-side as minority carriers and excess electrons diffuse from n-side to p-side.

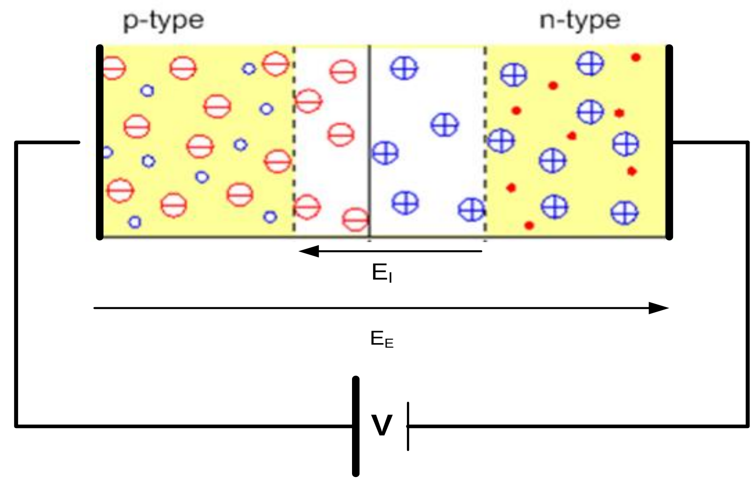


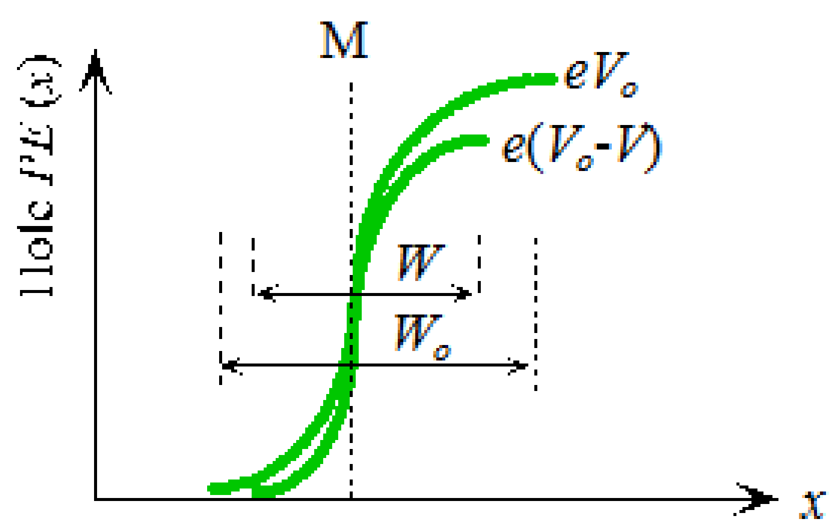
- Electrons injected in p-type region act as minority carriers -> diffuse towards positive terminal -> recombine with holes in this region -> lost holes replenished by positive terminal.



3. Operation of Diode (Forward Bias)

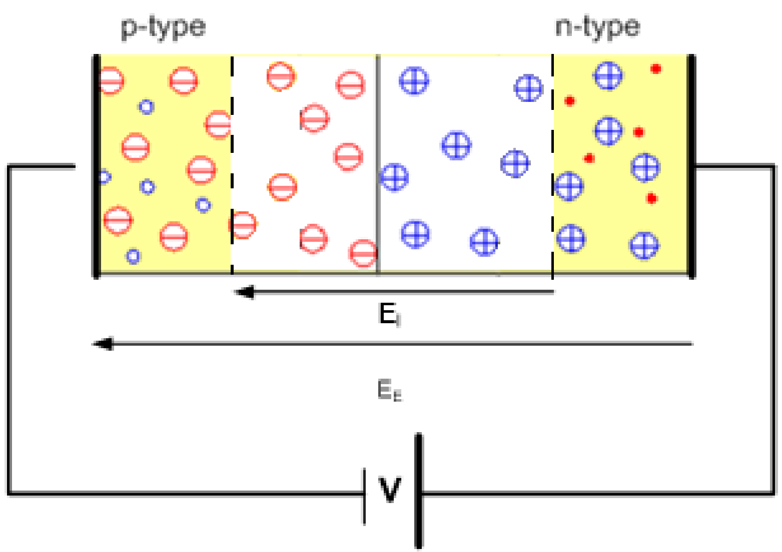
- Lost electrons replaced by more electrons diffusing in the junction -> replenished by electrons from negative terminal.
- The potential energy barriers are sustained by these processes, so current flows in the circuit and voltage drop exists across the junction.





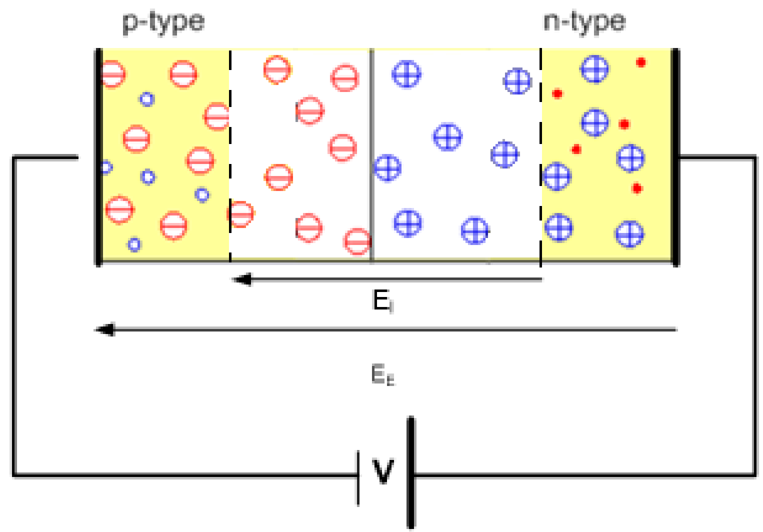
3. Operation of Diode (Reverse Bias)

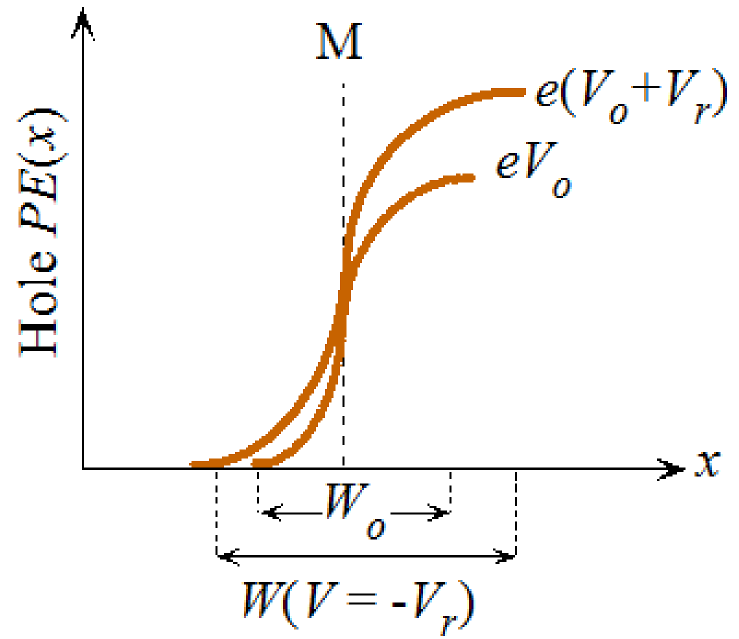
- For reverse bias condition, voltage drop is across depletion region.
- Negative battery terminal attract holes in p-side to move away from depletion region, while positive terminal attracts electrons from n-side.
- The effect is a widening of space charge layer on both sides of junction.



3. Operation of Diode (Reverse Bias)

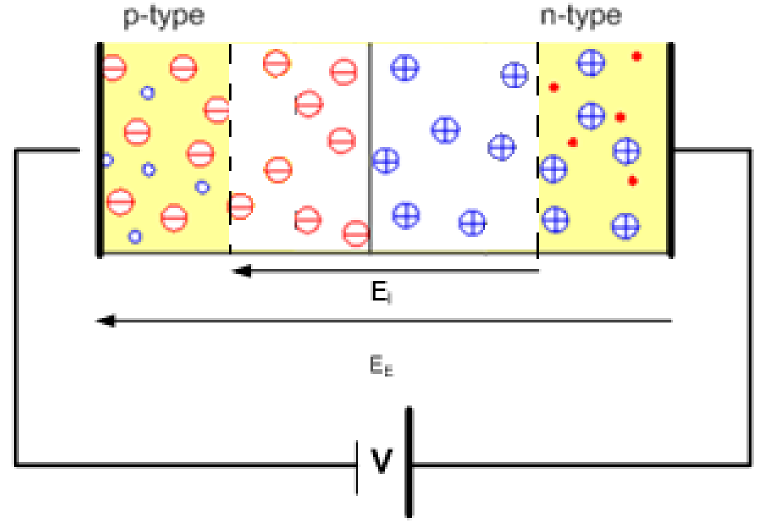
- For reverse bias condition, movement of electrons in n-side towards positive terminal and holes in p-side towards negative terminal is not sustainable -> no constant supplies of these carriers available.

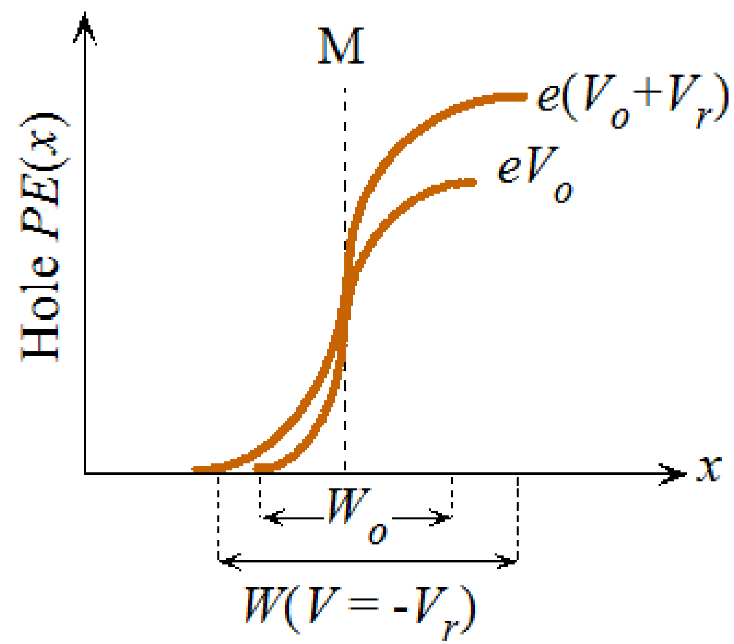




3. Operation of Diode (Reverse Bias)

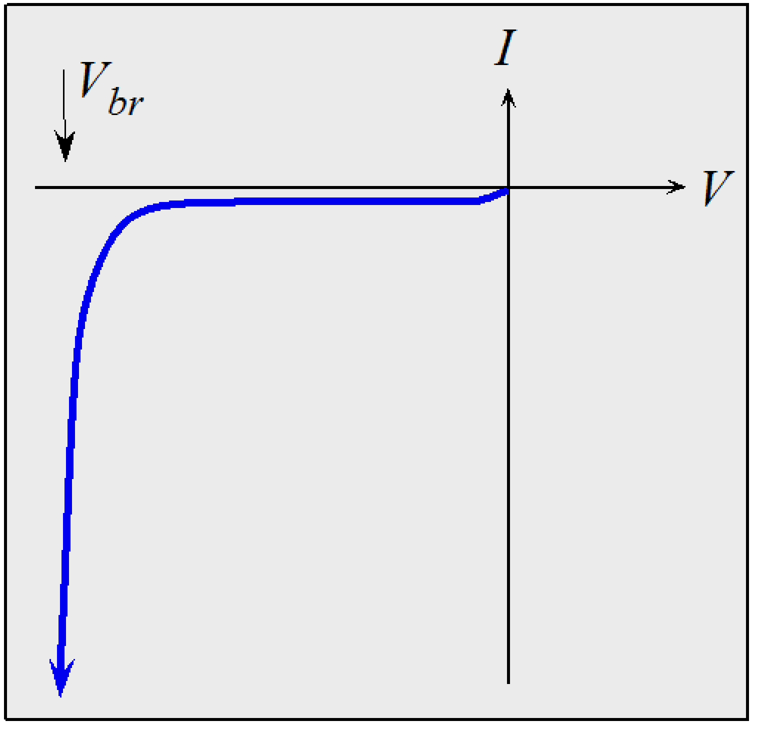
- Reverse bias voltage increases built in potential barrier and the electric field across the junction.
- Electrons which are minority carriers in p-side close to space-charge layer will be drifted across to n-side by the field -> a very small current (reverse saturation current).





3. Operation of Diode (Breakdown in the Reverse Bias Region)

- Breakdown can be due to: either avalanche breakdown or Zener breakdown.



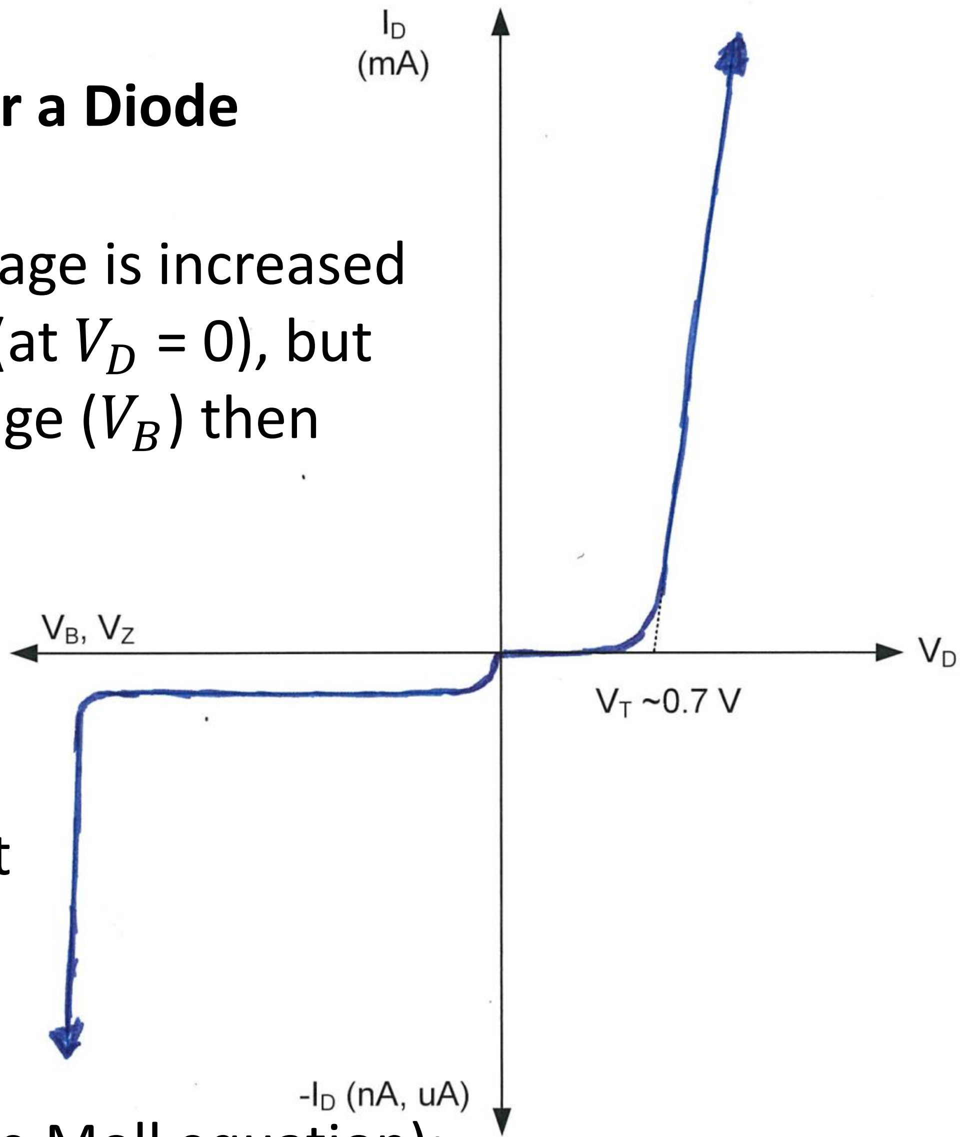
- Reverse voltage -> electric field -> velocity and kinetic energy of minority carriers (avalanche process) -> a dramatic increase in current -> increase in temperature -> destruction.

- Zener diode: its p-n junction is heavily doped in order to enhance breakdown (Zener breakdown) -> a type of diode for reverse bias breakdown conditions.

4. Current – Voltage Curve for a Diode

- *Forward bias*: applied voltage is increased from zero, current is zero (at V_D = 0), but after a breakthrough voltage (V_B) then increases exponentially.

- *Reverse bias*: a sharp increase in current as voltage is decreased from zero, but current settles at saturation current, then breakdown conditions.



- Current in the diode (Ebers-Moll equation):

$$I_D = I_S\left[e^{\left(\frac{V_D}{nV_T}\right)} - 1\right] = I_S e^{\left(\frac{V_D}{nV_T}\right)} - I_S$$

4. Current – Voltage Curve for a Diode (cont.)

- Ebers-Moll equation is used for modelling the characteristics of a PN based diode.

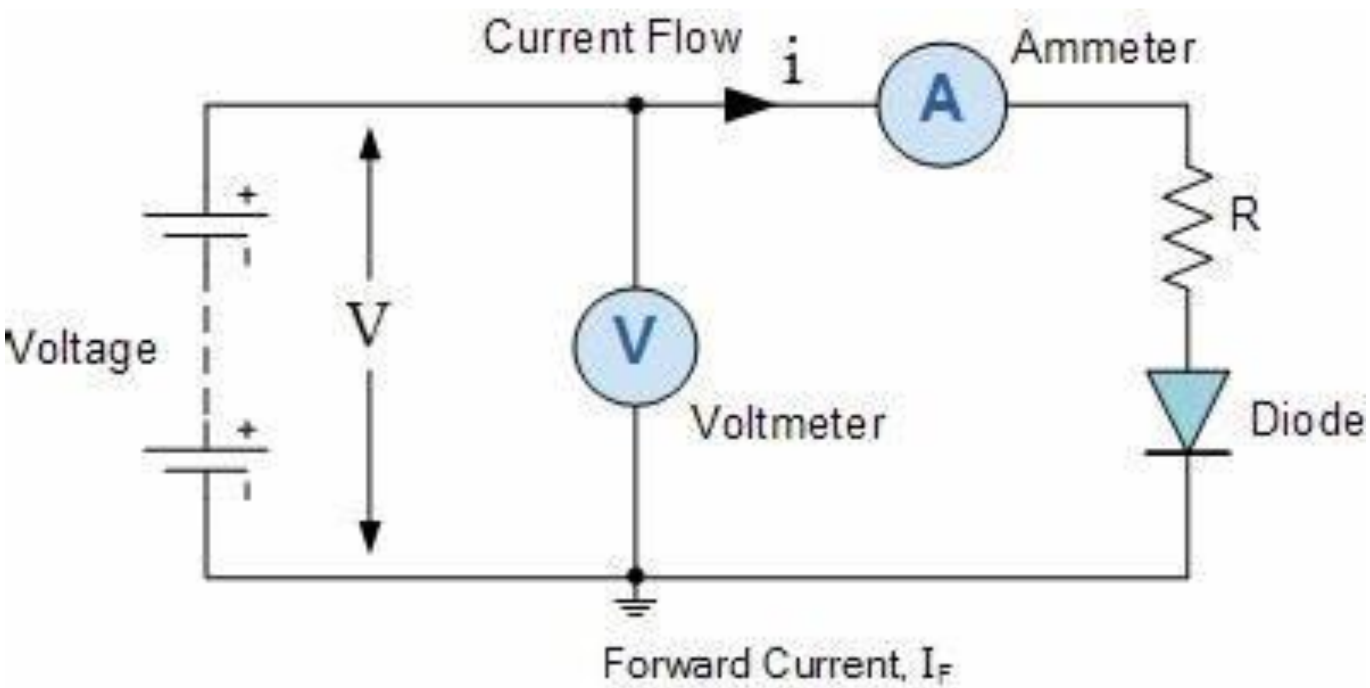
$$I_D = I_S\left[e^{\left(\frac{V_D}{nV_T}\right)} - 1\right] = I_S e^{\left(\frac{V_D}{nV_T}\right)} - I_S$$

Where:

- I_S = Reverse bias saturation current of the diode.
- V_D = Drop voltage of the diode.
- V_T = Thermal voltage factor (i.e. 25 mV at 25° C).
- n = Ideality factor od diode (its value is 1 to 2).

4. Current – Voltage Curve for a Diode (cont.)

- Set up a diode circuit experiment in the lab.
- Measure the voltage across and current that flows in the diode using voltmeter and ammeter respectively.



4. Current – Voltage Curve for a Diode (cont.)

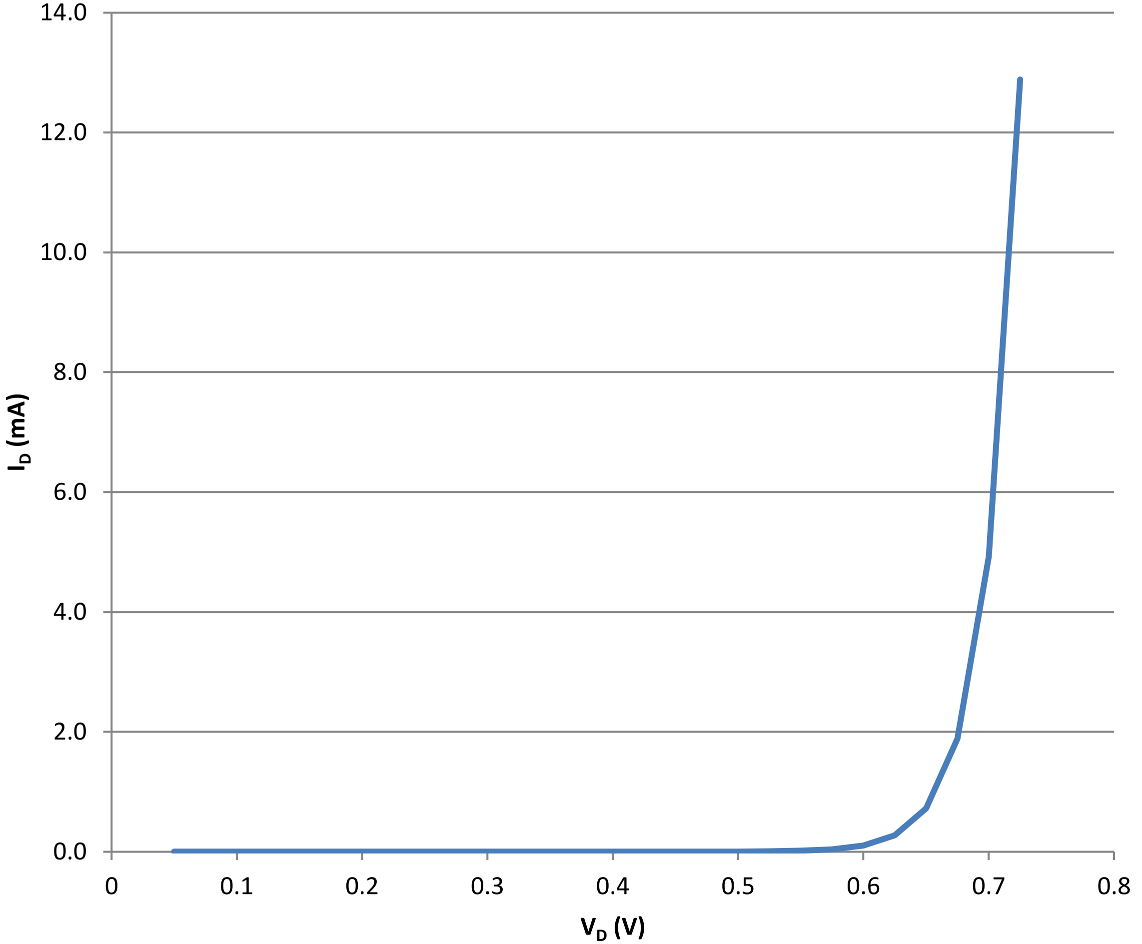
- Obtain the measurements data from experiment in the lab.

Parameter	Value	Unit
k	1.38×10^{-23}	
T	300	K
e	1.60×10^{-19}	C
N_a	1.00×10^{22}	m^{-3}
N_d	1.00×10^{22}	m^{-3}
n_i	1.00×10^{16}	m^{-3}
V_0	0.71	V
I_s	1.00×10^{-14}	A
V_T	0.026	V

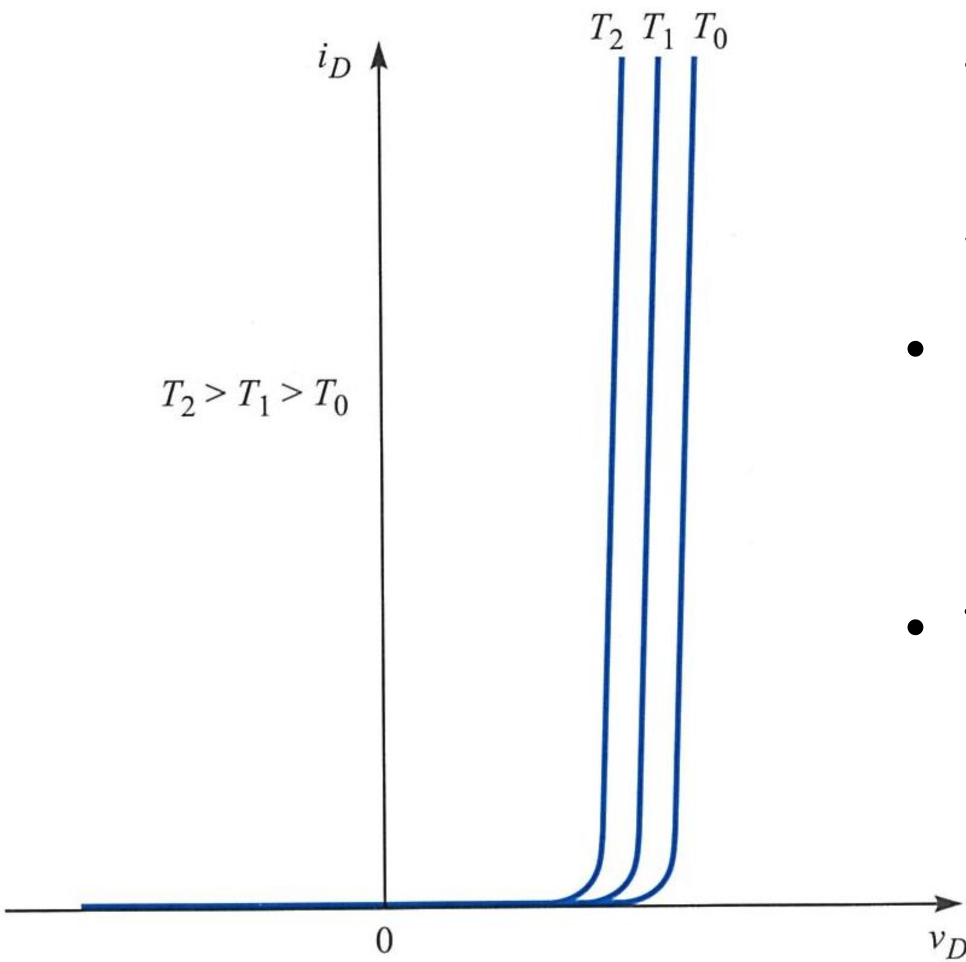
Vd (V)	Id (mA)
0.05	5.84E-11
0.1	4.58E-10
0.15	3.19E-09
0.2	2.19E-08
0.25	1.50E-07
0.3	1.03E-06
0.35	7.02E-06
0.4	4.80E-05
0.45	3.29E-04
0.475	8.59E-04
0.5	2.25E-03
0.525	5.88E-03
0.55	1.54E-02
0.575	4.02E-02
0.6	1.05E-01
0.625	2.75E-01
0.65	7.20E-01
0.675	1.88E+00
0.7	4.93E+00
0.725	1.29E+01
0.75	3.37E+01
0.775	8.82E+01
0.8	2.31E+02

4. Current – Voltage Curve for a Diode (cont.)

- Using data obtained from the experiment, draw and simulate the I-V curve of the diode.



4. Current – Voltage Curve for a Diode (Influence of Temperature on the Diode Curve)



- For forward bias, increasing the operating temperature -> reducing the turning on voltage of diode.
- Reverse bias diode current will double for every 10°C rise in temperature.
- Thermal voltage of diode:

$$V_0 = \frac{kT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$= V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

Example for Tutorial 3:

At a temperature of 27°C (i.e. common temperature for components in an enclosed operating system), determine the thermal voltage V_T of a semiconductor device. [2.5 marks]

$$V_T = \frac{kT_K}{q}$$

Where:

k = Boltzman coefficient (1.38×10^{-23}).

e = Electron charge (1.60×10^{-19}).

T_k = Temperature in Kelvin.

- Converting the temperature in Celsius to Kelvin, we obtain:

$$T = 273 + {}^\circ\mathrm{C} = 273 + 27 = 300^\circ\mathrm{K}$$

- Thus, the thermal voltage of the semiconductor device is:

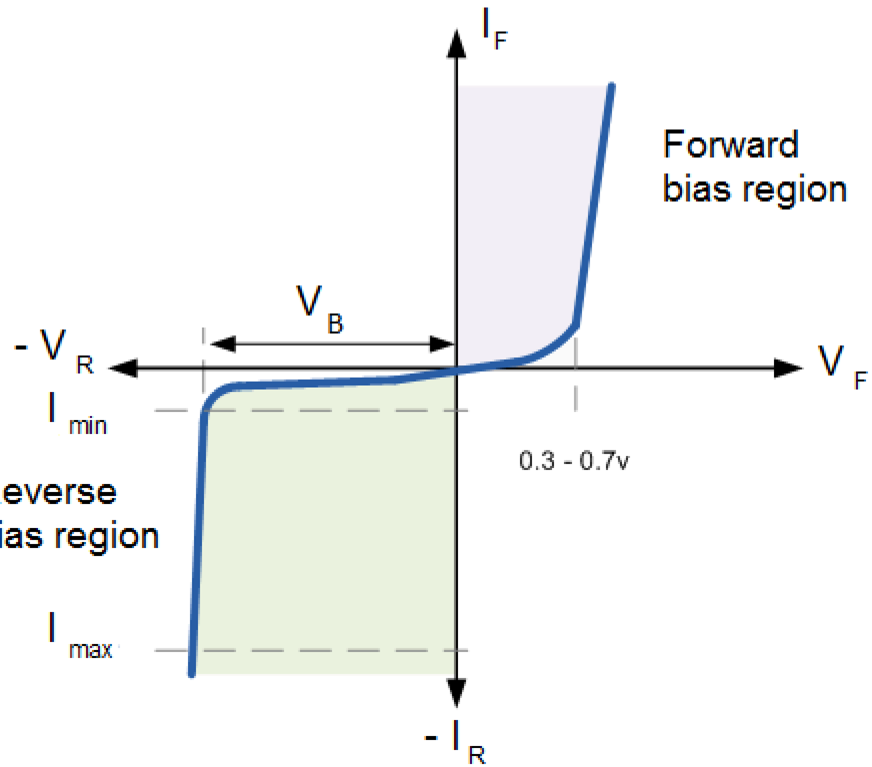
$$V_T = \frac{kT_K}{q}$$

$$= \frac{(1.38 \times 10^{-23} J/K)(300^\circ\mathrm{K})}{1.6 \times 10^{-19}\mathrm{C}} \cong 26\ \mathrm{mV}$$

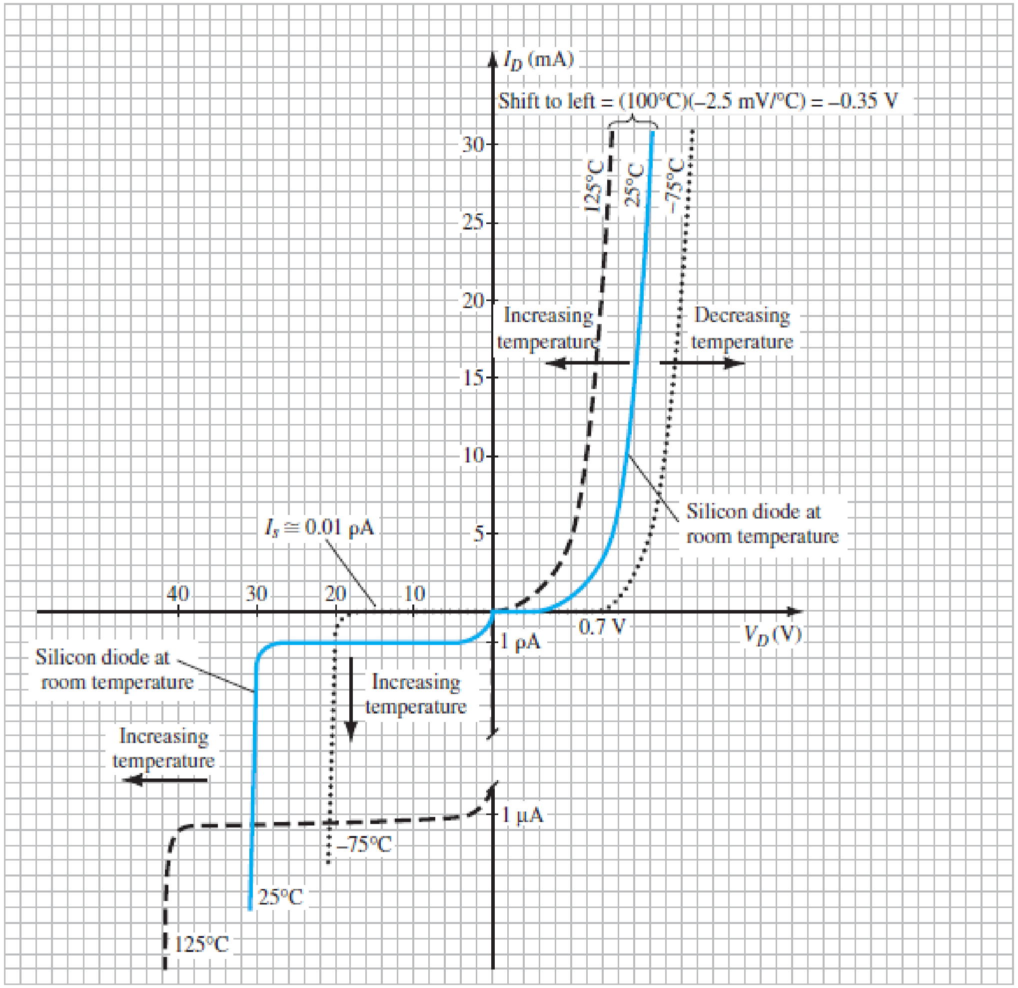
- As a result, the thermal voltage of the device is found to be approximately 26 mV.

Example for Tutorial 4

Given a V-I curve graph, briefly explain how temperature influences diode characteristics. [5 marks]



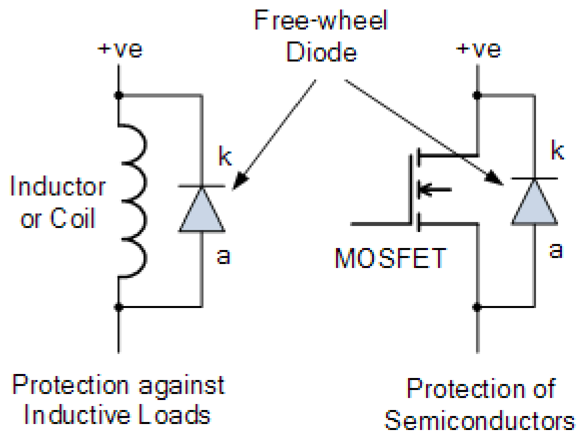
- A V-I curve graph is as shown in the figure below.



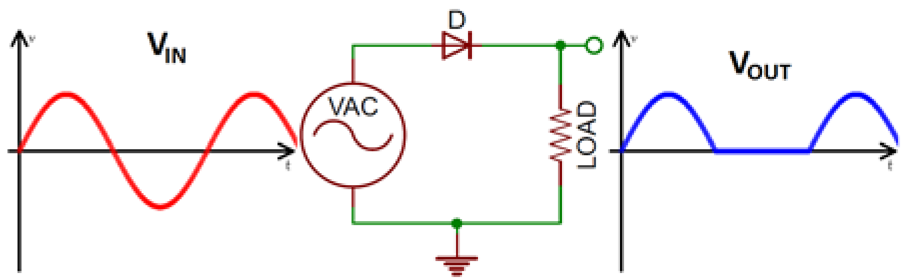
- Temperature could influence the V-I curve: Increasing the temperature could shift the curve towards Y-axis in the plot. [2.5]
- This would make the forward bias voltage of the diode less than before and therefore the reverse bias voltage would increase slightly.
- Decreasing the temperature would provide the opposite effect towards the temperature characteristics of the diode. [2.5]

5. Some Applications of Diode

- Restrict the flow of current in one direction – snubber/free wheel applications.

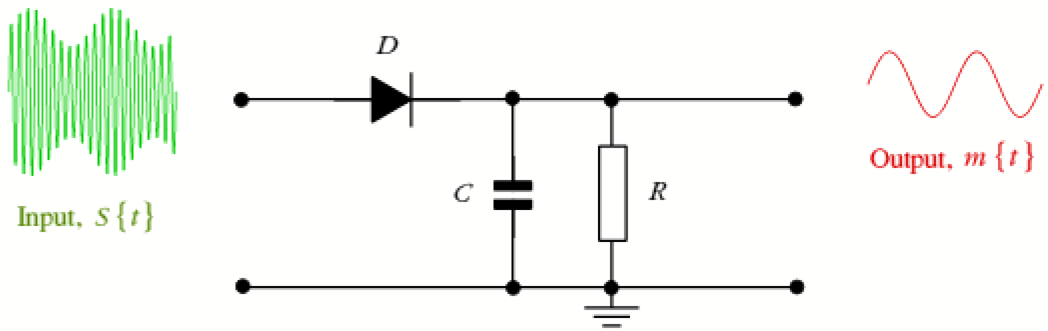


- Rectifiers – AC to DC conversion (electronic chargers).
- Voltage limiters and regulators.



5. Some Applications of Diode (cont.)

- AM detectors.



- Light emitting diodes (LED).
- Photodiodes and solar cells.