Physics: E-103

Textbook:

- Robert L. Boylestad and Louis Nashelsky, *Electronic Devices and Circuit Theory*, 7th or 10th or 11th Edition.

References:

- Sedra and Smith, *Microelectronic Circuits*, Oxford University Press, *Sixth Edition*,2010.
- Behzad Razavi, *Fundamentals of Microelectronics*, John Wiley & Sons, Preview Edition, 2006
- Jimmie J. Cathey, Ph.D, *Theory and Problems of Electronic Devices and Circuits*, 2nd Edition, 2002.
- Any other materials available on the web.

Syllabus:

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Chapter 1: Introduction:

1.1 Introduction

Different models have been suggested for atom representation among them Rutherford (1911) and Bohr (1913). According to Bohr model:

1. The atom has a massive positively-charged nucleus;
2. The electrons revolve round their nucleus in circular orbits, the centrifugal force being balanced by the electrostatic pull between the nucleus and electrons;
3. While revolving in these permitted stationary (or stable) orbits, the electron does not radiate out any electromagnetic energy.
4. The atom radiates out energy only when an electron *jumps* from one orbit to another.

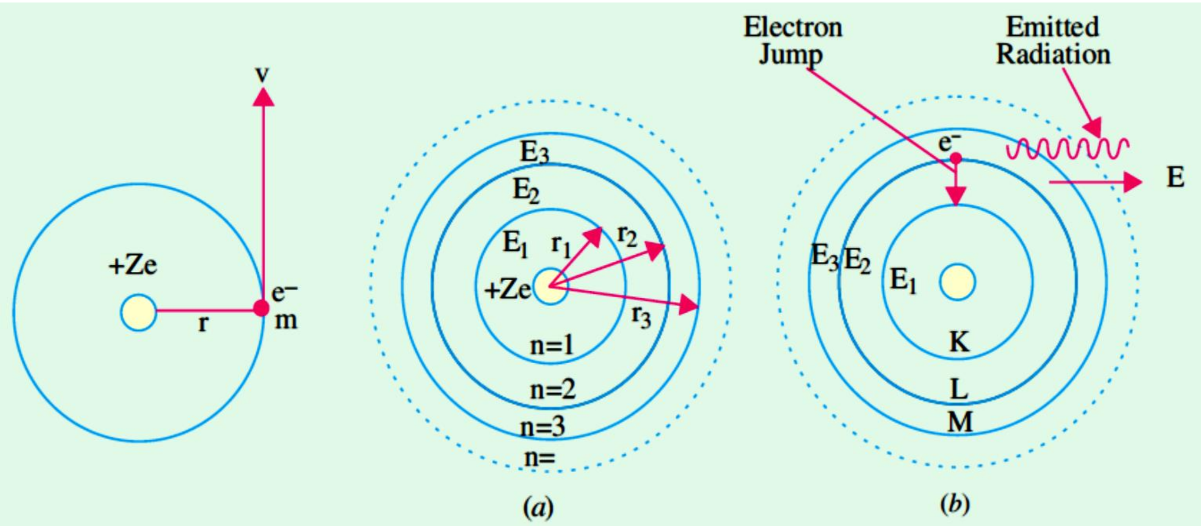


Figure 1.1: Bohr Atomic model.

Shell n	K 1	L 2	M 3	N 4
Total No. of electrons = $2n^2$	2	8	18	32

Figure 1.2: Atom shells and sub-shells.

1.2 Insulators, Conductors and Semiconductors

The electrical conduction properties of different elements and compounds can be explained in terms of the electrons having energies in the valence and conduction bands. The electrons lying in the lower energy bands, which are normally filled, play no part in the conduction process.

- **Insulators. Figure 1.3-a**
    - Insulators are those materials in which valence electrons are bound very tightly to their parents' atoms, thus requiring very large electric field to remove them from the attraction of their nuclei.
    - Insulators have no free charge carriers available with them under normal conditions.
    - Insulators (Figure 1.3 - *a*) have a full valence band, have an empty conduction band, have a large energy gap (of several eV) between them and at ordinary temperatures.
    - For conduction to take place, electrons must be given sufficient energy to jump from the valence band to the conduction band. Increase in temperature enables some electrons to go to the conduction band.

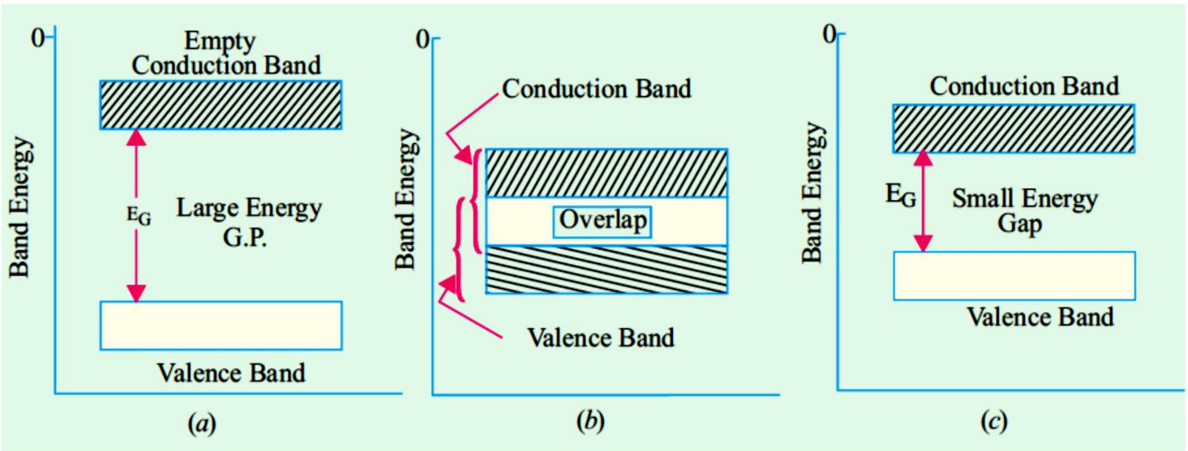


Figure 1.3: Energy bands.

- **Conductors. Figure 1.3-b**
    - Conducting materials are those in which plenty of free electrons are available for electric conduction.
    - In terms of energy bands, it means that electrical conductors are those which have overlapping valence and conduction bands.

- Availability of a large number of conduction electrons.
- The absence of forbidden energy gap in good conductors.
- The total current in such conductors is simply a flow of electrons.

➢ **Semiconductors. Figure 1.3-c**

- A semiconductor material is one whose electrical properties lie in between those of insulators and good conductors. **Examples are: Germanium and Silicon.**
- In terms of energy bands, semiconductors can be defined as those materials which have almost an empty conduction band and almost filled valence band
- A very narrow energy gap (of the order of 1 eV (1 eV= 1.6×10^{-19} Joule)) separating the Conduction and Valance bands.
- At 0ºK, there are no electrons in the conduction band and the valence band is completely filled. However, with increase in temperature, width of the forbidden energy bands is decreased so that some of the electrons are liberated into the conduction band.
- Conductivity of semiconductors increases with temperature. Moreover, such departing electrons leave behind positive holes in the valence band. Hence, semiconductor current is the sum of electron and hole currents flowing in opposite directions.

➢ **Note:**

Ge: Has 32 Electrons

Si: Has 14 Electrons

1.2.1 Types of Semiconductors

- Intrinsic or Pure Semiconductors (اشباه الموصلات النقية
- Extrinsic or Impure Semiconductors (اشباه الموصلات غير النقية) : N-Type and P-Type

1.2.1.1 Intrinsic Semiconductors

- An intrinsic semiconductor is one which is made of the semiconductor material in its extremely pure form. Common examples of such semiconductors are : pure germanium and silicon which have narrow forbidden energy gaps .
- The energy gap is so small that even at ordinary room temperature.

- There are many electrons which possess sufficient energy to jump across the small energy gap between the valence and the conduction bands.
- For each electron liberated into the conduction band, a positively charged hole is created in the valence band.
- Semiconductor current consists of movement of electrons and holes in opposite directions (holes and Electrons). Electron current is due to movement of electrons in the conduction band whereas hole current is within the valence band as a result of the holes 'jumping' from one atom to another.

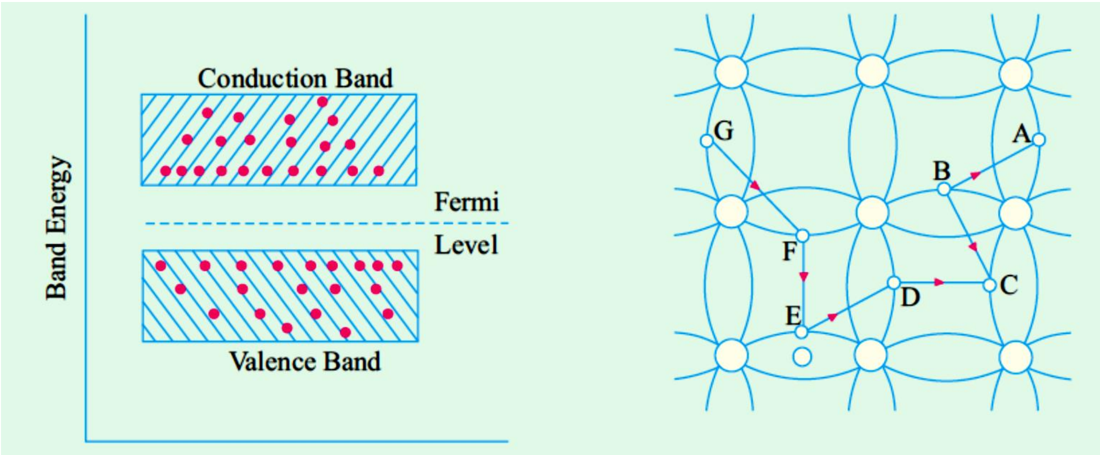


Figure 1.4: Hole Formation in Semiconductors

Hole Formation in Semiconductors: From Figure 1.4, suppose the covalent bond is broken at *A* and the electron has moved through the crystal lattice leaving behind a hole in the covalent bond. An electron at *B* may jump into the vacant hole at *A* and later, an electron at *C* may jump into the hole at *B* and so on. In this way, by a succession of electron movements, a hole will appear at *G* and a negative charge would have moved from *G* to *A*

- Note: Fermi level may be defined as the energy which corresponds to the centre of gravity of conduction electrons and holes weighted according to their energies.

1.2.1.2 Extrinsic Semiconductors

Extrinsic semiconductor: It is an intrinsic semiconductor with some **added suitable impurity (شوائب) or doping agent or dopant.**

The usual doping agents are:

1. ***Pentavalent*** atoms having five valence electrons (arsenic, antimony, phosphorus) or

2. ***Trivalent*** atoms having three valence electrons (gallium, indium, aluminium, boron).

Pentavalent doping atom (ذرات خماسية التكافؤ) is known as ***donor*** atom because it donates or contributes one electron to the conduction band of pure germanium.

The trivalent atom (ذرات ثلاثية التكافؤ), on the other hand, is called ***acceptor*** atom because it accepts one electron from the germanium atom.

Depending on the type of doping material used, extrinsic semiconductors can be sub-divided into two classes : ***(i)*** *N*-type semiconductors and ***(ii)*** *P*-type semiconductors.

- **الذرات خماسية التكافؤ هي الذرات التي تحتوي على خمسة الكترونات في المدار الخارجي**
- **الذرات ثلاثية التكافؤ هي الذرات التي تحتوي على ثلاثة الكترونات في المدار الخارجي**

(*a*) *N*-type Extrinsic Semiconductor. This type of semiconductor is obtained when a **pentavalent material** like Antimony (Sb) (51 Electrons) is added to pure germanium crystal. As shown in Figure 1.5 (*a*), each antimony atom forms covalent bonds with the surrounding four germanium atoms with the help of four of its five electrons. The fifth electron is superfluous and is loosely bound to the antimony atom. Antimony is called ***donor (واهب)*** impurity and makes the pure germanium an *N*-type (*N* for negative) extrinsic semi-conductor.

It is seen from the above description that in *N*-type semiconductors, electrons ***are the majority carriers(الاغلبية)*** while holes constitute the **minority carriers(الاقلية)** .

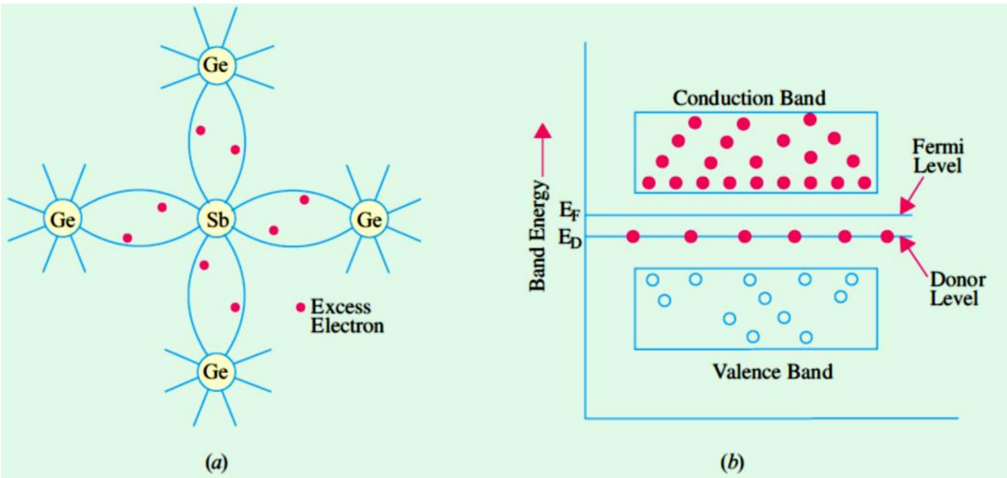


Figure 1.5: N-Type Semiconductors

(*b*) *P*-type Extrinsic Semiconductor. This type of semiconductor is obtained when traces of a trivalent like boron (*B*) (**5 Electrons)**)are added to a pure germanium crystal.

In this case, the three valence electrons of boron atom form covalent bonds with four surrounding germanium atoms but one bond is left incomplete and gives rise to a hole as shown in Figure 1.6 (*a*). Thus, boron which is called an ***acceptor*** impurity causes as many positive holes in a germanium crystal as there are boron atoms thereby producing a *P*-type (*P* for positive) extrinsic semiconductor.

In this type of semiconductor, conduction is by the movement of holes in the valence band.

Accordingly, holes form the majority carriers *whereas electrons constitute minority carriers*.

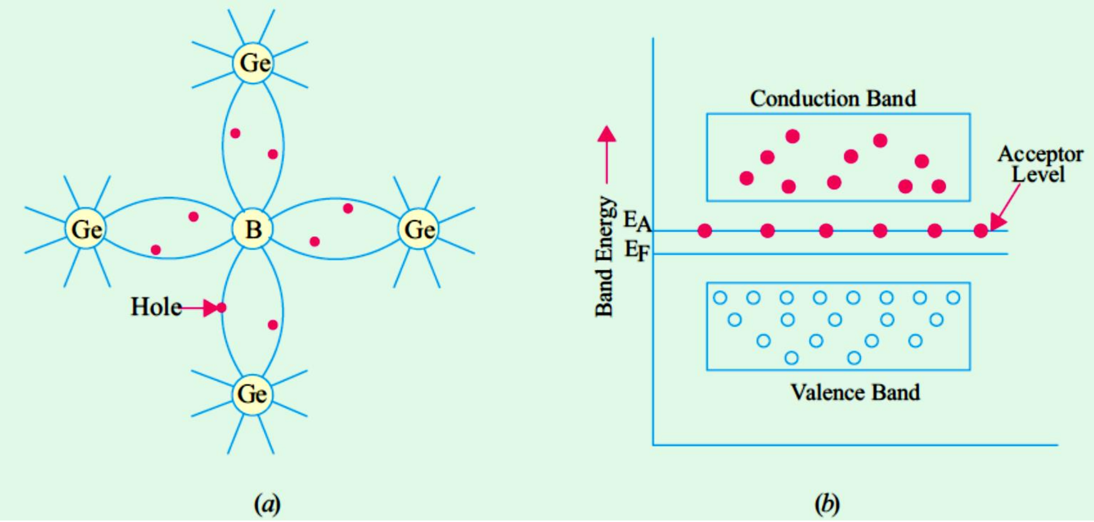


Figure 1.6: P-Type Semiconductors.

1.2.2 Majority and Minority Charge Carriers (حاملات الشحنة الاقلية والاغلبية)

Semiconductor Type **نوع اشباه الموصلات**	**Majority Carriers** **حالامت الشحنة الاغلبية**	**Minority Carriers** **حاملات الشحنة الاقلية**
N-Type	Electrons (-)الالكترونات سالبة الشحنة	Holes (+)الحفر موجبة الشحنة
P-Type	Holes (+)الحفر موجبة الشحنة	Electrons (-) الالكترونات سالبة الشحنة

1.2.3 Diffusion

It is the diffusion of charge from a region of high charge density to one of low charge density.

(انتقال الشحنات بدون تاثير خارجي.. انتقال الشحنات من منطقة تركيز الشحنات العالي الى الواطئ)

1.2.4 Drift

Charge drift under the influence of applied electric field

(انتقال او حركة الشحنات بتاثير مجال او فولتية خارجية)

1.3 PN Junction

Semiconductor junction diodes are made by joining two semiconductors together. A *pn* junction diode is formed by joining a "*p*-type" semiconductor to an "*n*-type" semiconductor:

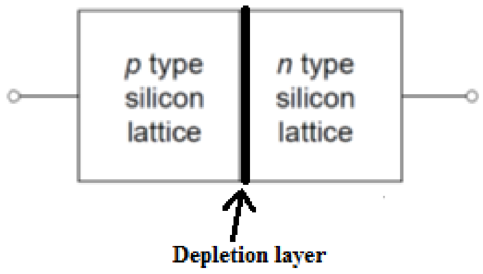


Figure 1.7: PN-Junction.

This contact region between the *p* and *n* regions is called the **depletion region**.

منطقة او طبقة الاستنزاف

1.3.1 *Reverse and Forward Biased Junction*

There are two important states for a *pn* junction, the reversed biased and forward biased states:

(1) Forward biased PN-Junction:

The forward biased PN-Junction is shown in Figure 1.8 (*a*).

(i) The holes are ***pushed*** by the positive battery terminal and electrons by the negative battery terminal with the result that both the electrons and the holes are driven ***towards*** the junction where they recombine. The junction offers ***low resistance*** in the forward direction.

(ii) Another way to explain current flow in forward direction is to say that forward bias of V volts lowers the barrier potential to $(V - V_B)$ which now allows more current to flow across the junction.

Thus, the forward bias reduces the thickness of the depletion layer.

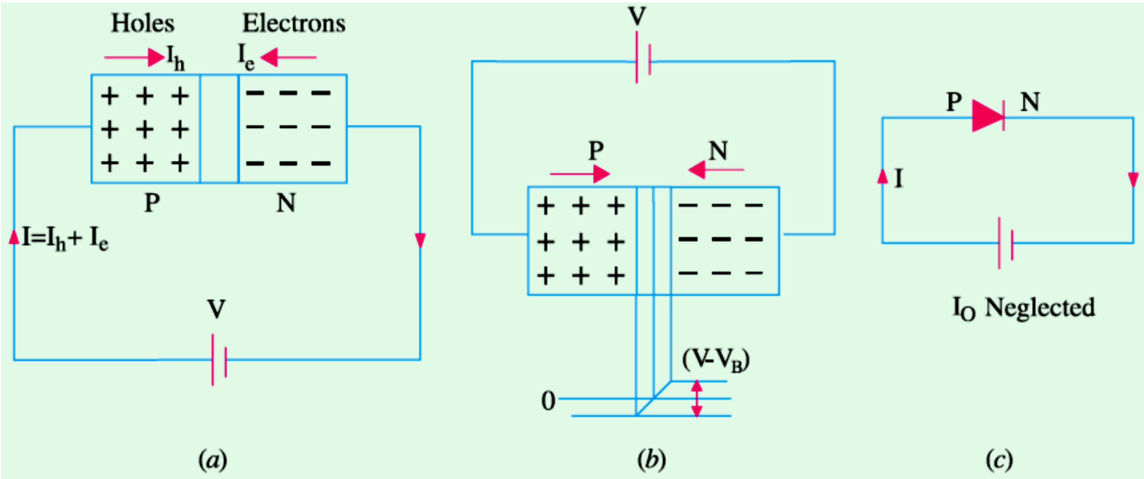


Figure 1.8: Forward biased PN-Junction.

(2) Reverse biased PN-Junction:

The reverse biased PN-Junction is shown in Figure 1.9 (*a*). In this case both holes and electrons move ***away*** from the junction and ***away*** from each other. Since there is no electron-hole combination, no current flows and the junction offers high resistance.

Another way of looking at the process is that in this case, the applied voltage increases the barrier potential to $(V + V_B)$, thereby blocking the flow of majority carriers.

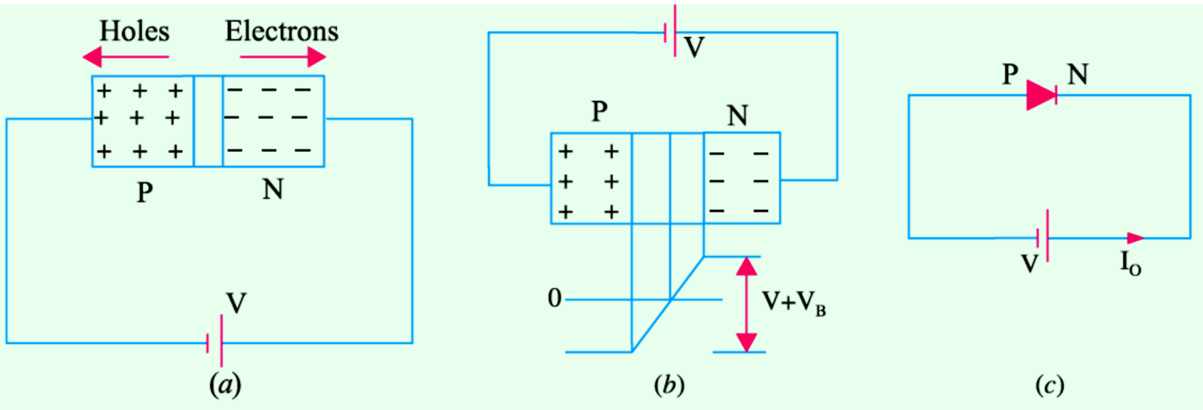


Figure 1.9: Reverse biased PN-Junction.

1.4 Diodes (PN Junction)

Diodes are made from two different types of semiconducting materials that come together to form a “junction”:

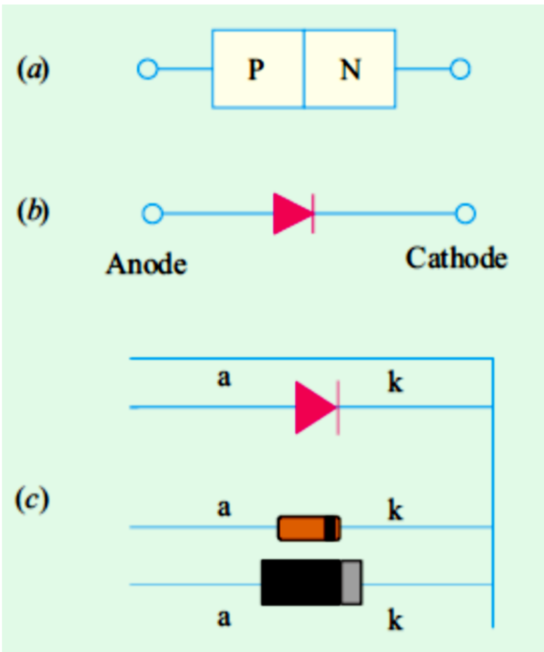


Figure 1.10: Diode.

1.4.1 Ideal Diode

- $V_i < 0 \Rightarrow i = 0$. In this region, the diode is "off."
- $V_i > 0 \Rightarrow i > 0$. In this region, the diode is "on."

1.4.2 Physical Operation of Diodes (Diode operation Regions)

مناطق عمل الدايود

Real diodes have a more complicated *i-v* characteristic curve than ideal diodes. As shown in the text for a silicon diode (Figure 1.11).

The diode has three distinct regions of operation:

1. **Forward bias:** When the diode is forward-biased and the applied voltage is increased from zero, hardly any current flows through the device in the beginning. It is so because the external voltage is being opposed by the internal barrier voltage V_B **whose value is 0.7 V for Si and 0.3 V for Ge.** As soon as V_B is neutralized, current through the diode increases rapidly with increasing applied battery voltage.
2. **Reverse bias:** When the diode is reverse-biased, majority carriers are blocked and only a small current (due to minority carriers) flows through the diode. As the reverse voltage is increased from zero, the reverse current very quickly reaches its maximum or saturation value I_0 which is also known as ***leakage current***. It is of the order of nanoamperes for Si and microamperes for Ge. The value of I_0 (or I_s) is independent of the applied reverse voltage but depends on:

(***a***) Temperature. (***b***) Degree of doping. (***c***) Physical size of the junction.

3. **Breakdown region**: As seen from Figure 1.11, when reverse voltage exceeds a certain value called break-down voltage V_{BR} (or Zener voltage V_z), the leakage current suddenly and sharply increases, the curve indicating zero resistance at this point. Any further increase in voltage is likely to produce burnout unless protected

- These characteristics can be described by the analytical equation called ***Boltzmann diode equation*** given below

$$I = I_0\left(e^{\frac{v}{\eta V_T}} - 1\right)$$

where

- η = "emission constant." = 1 – for germanium and = 2 – for silicon.
- $V_T = kT/q \approx 25$ mV at room temperature (300 Kelvin). Called the "thermal voltage."

k=Boltzmann's constant=1.38×10^{-23} *j/k*

T=Temperature in Kelvin., q= Electron charge= 1.6×10^{-19} *C*

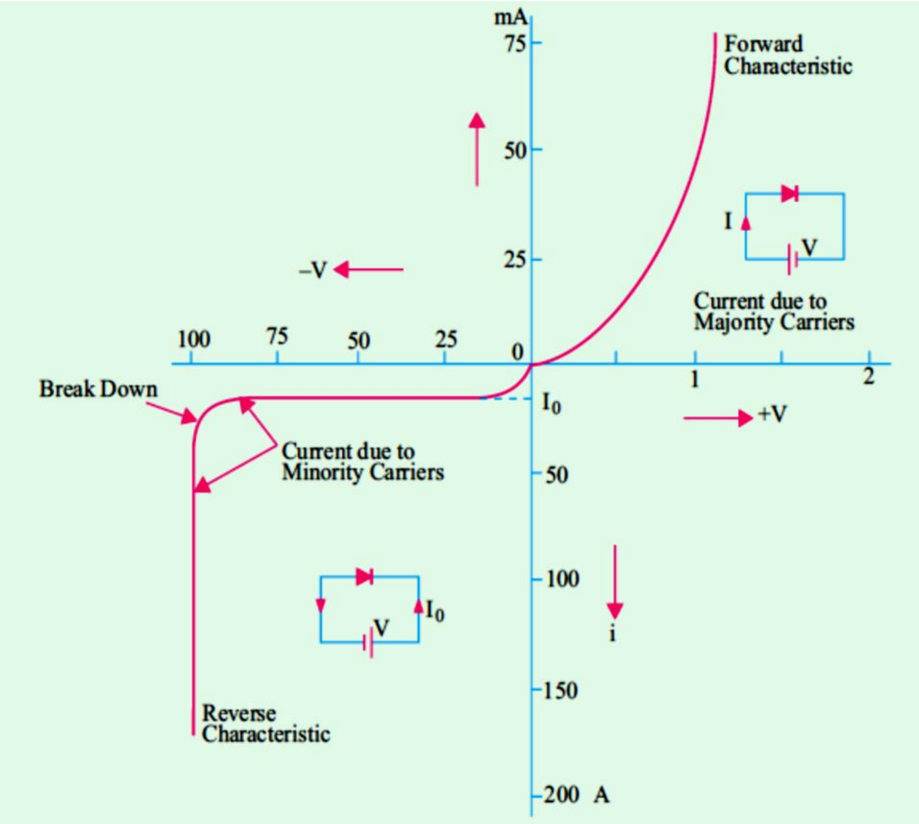
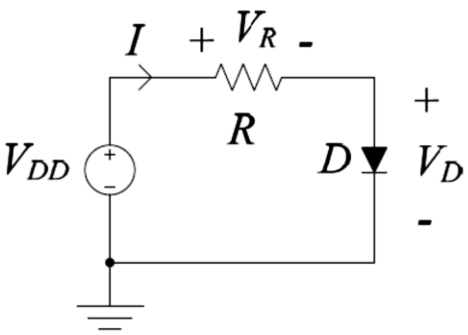


Figure 1.11: Real diode *i*-*v* characteristic curve.

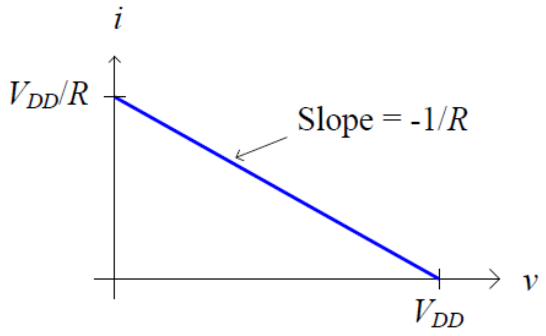
1.4.3 DC Analysis of Diode Circuits (DC Load Line)



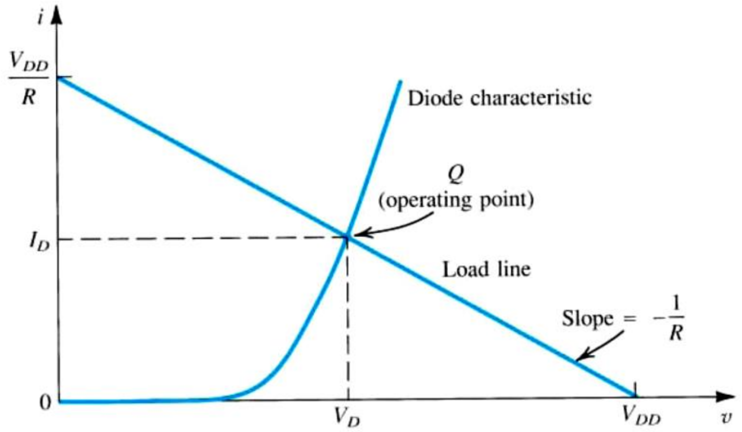
By applying KVL we get:

$$V_{DD} = IR + V_D$$

This equation represents the DC load line as shown below:

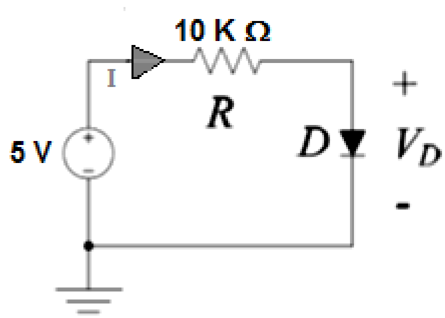


Now plot the diode characteristic curve and the load line in the same graph as shown below:



Q-point is the operating point (نقطة العمل)

Example: Plot the DC load line for the following circuit:



Solution:

Apply KVL :

$5V - 10K \times I - V_D = 0$

Then:

If I=0:

$5V - 10K \times 0 - V_D = 0$

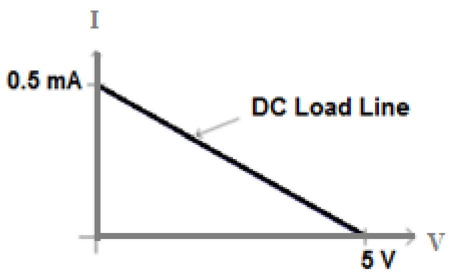
$V_D = 5V$

If V_D=0;

$5V - 10K \times I - 0 = 0$

$I = \frac{5\ V}{10\ K} = 0.5\ m\ A$

Then the DC load line is:



Example: Resolve the current I and the voltage V for the two circuits (Assume ideal diodes)

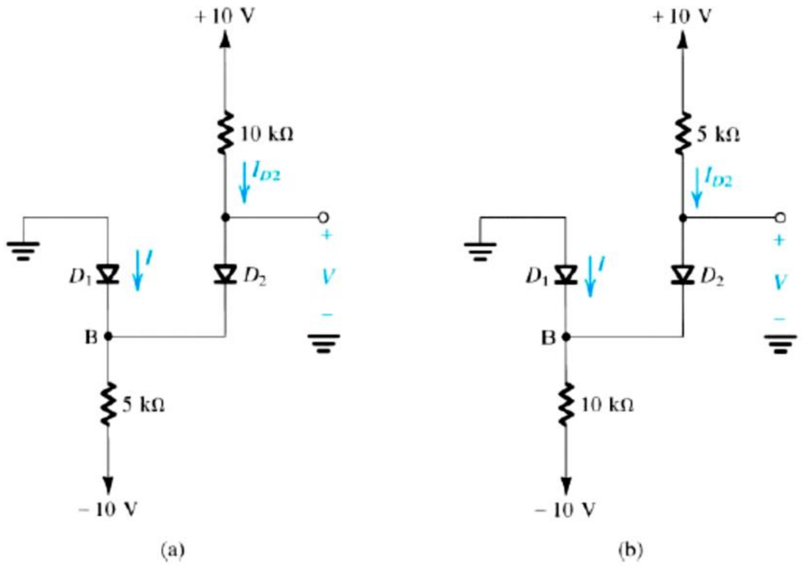


Figure a:

Assume the two diodes are forward biased (short circuit and V=0), thus:

$$I_{D2} = \frac{10-0}{10} = 1\text{mA}.$$

Then, Apply KCL at node B:

$$I + 1 = \frac{0-(-10)}{5} \Rightarrow I = 1\text{mA}.$$

Thus, both D1 and D2 are conducting as originally assumed.

Figure b:

Assume the two diodes are forward biased (short circuit and V=0), thus:

$$I_{D2} = \frac{10-0}{5} = 2\text{mA}.$$

Then,
$$I + 2 = \frac{0-(-10)}{10} \Rightarrow I = -1\text{mA}.$$

Since this is not possible, the assumption is invalid. To obtain a consistent solution, the assumption is modified in such a way that D1 is off. As a result:

$$I_{D2} = \frac{10-(-10)}{15} = 1.33\text{mA}.$$

$$V = V_B = -10 + 1.33 \times 10 = 3.3\text{V}.$$

1.4.4 *Approximate Diode Circuit Solutions*

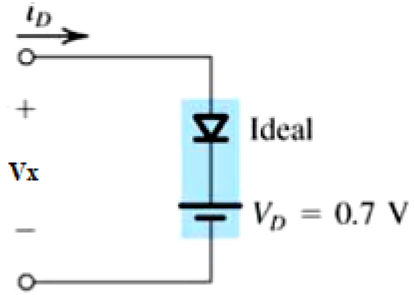
The approximate diode models are: 1. Constant-Voltage-Drop (CVD) Model. 2. Piecewise Linear (PWL) Model. 3. Small signal

1. Constant-Voltage-Drop (CVD) Model:

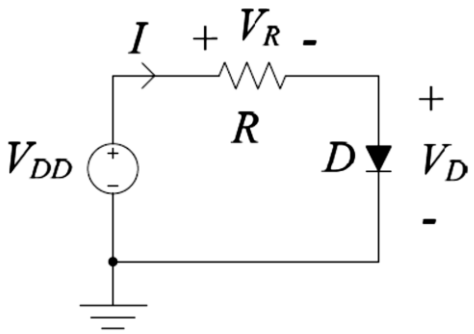
The Diode is ON when Vx > V_D

V_D = 0.7 V for Si-Diode

V_D = 0.3 V for Ge-Diode

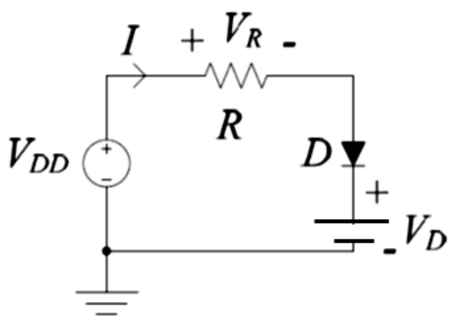


Example: Find the value of the current *I* in the circuit below using the CVD model for a silicon diode if R=2 K Ohm and V_{DD}=4 and 0.4 Volts.



Solution:

Using the CVD model, the equivalent circuit will be:



Applying KVL:

- **V_{DD}= 4 V**

  $4 = I \times 2K + 0.7$

  I=1.65 mA (forward biased diode)

- **V_{DD}= 0.4 V**

  $0.4 = I \times 2K + 0.7$

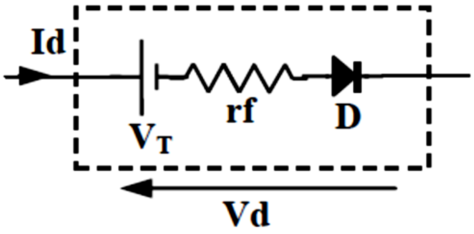
  I= - 0.15 mA (reverse biased)

  In this case, as the current is negative, thus the diode must be reversed biased and the current in this case should be 0 Amp.

2. **Piecewise Linear (PWL) Diode Model**: This is a “battery plus internal diode resistance model.” It is one step better than the CVD model

في هذا النموذج تكون الدائرة المكافئة للدايود هي فولتية + مقاومة داخلية كما مبين في الشكل التالي:

الفولتية هي اما 0.7 او 0.3 حسب نوع الدايود



3. Small Signal Model: or AC Model

• Small signal model is used for the applications in which a diode is biased to operate in the forward region and a small AC signal is superimposed on the dc quantities.

(يستخدم هذا النموذج عند وجود مصدرين للفولتية احدهما AC والثاني DC)

• **Small signal analysis**

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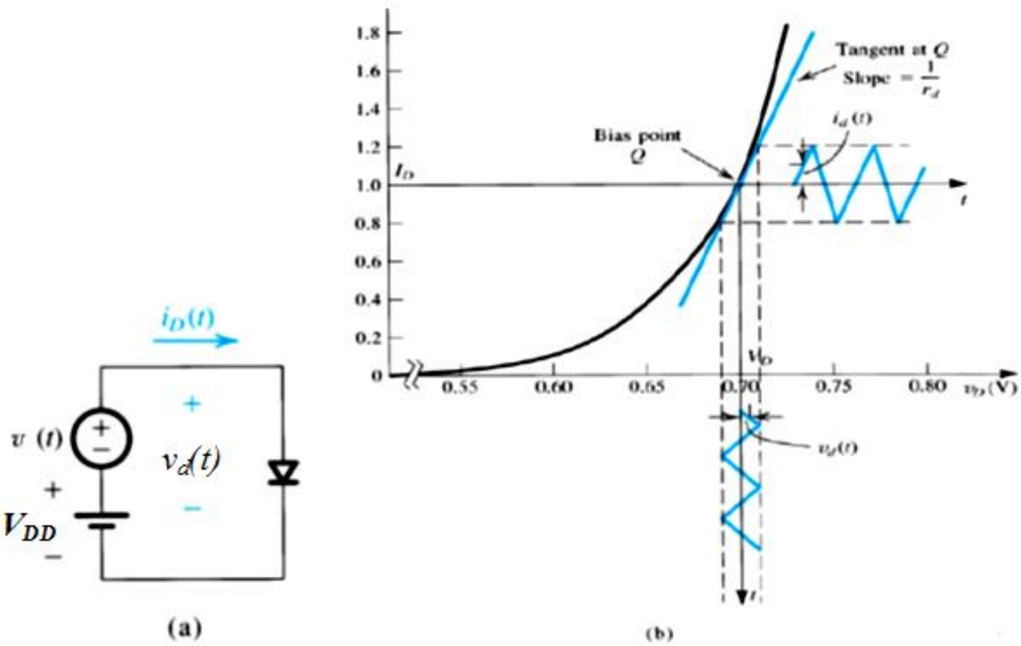
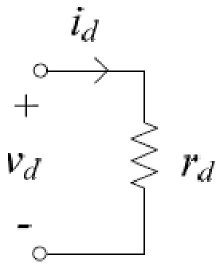


The equivalent circuit for the small-signal operation of diodes is:

هنا تعتبر الدائرة المكافئة هي مقاومة الدايود rd والتي يتم حسابها كما يلي:



r_d is called the small signal resistance or AC resistance of the diode. It can be computed as follows:

$$I = I_0\left(e^{\frac{v}{\eta V_T}} - 1\right)$$

$$\frac{dI}{dv} = \frac{d}{dv}\left(I_0\left(e^{\frac{v}{\eta V_T}} - 1\right)\right)$$

$$= \frac{1}{\eta V_T} I_0 e^{\frac{v}{\eta V_T}}$$

$$= \frac{1}{\eta V_T}(I + I_0),$$

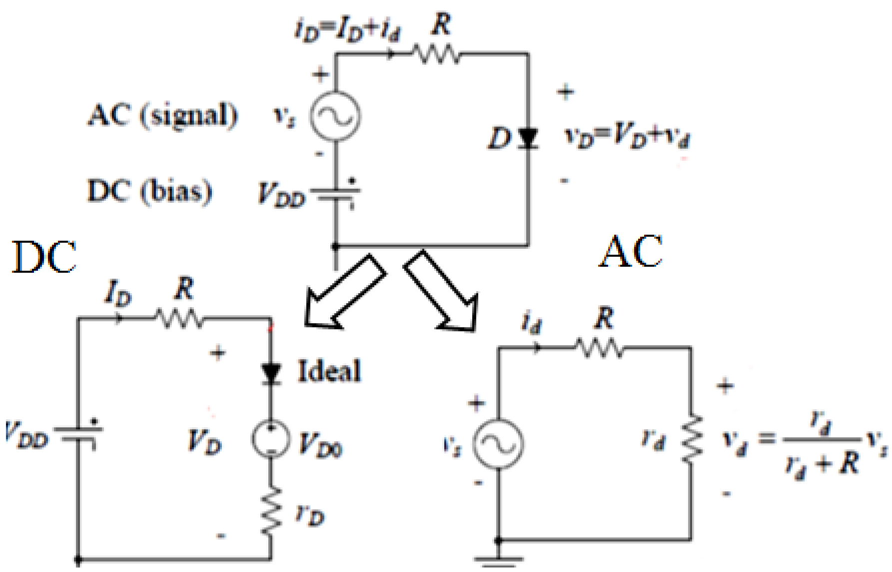
$as\ I \gg I_0$, then:

$$\frac{dI}{dv} \cong \frac{I}{\eta V_T}$$

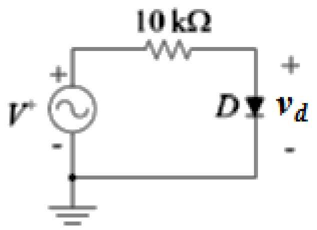
$$\frac{dv}{dI} = r_d = \frac{\eta V_T}{I}$$

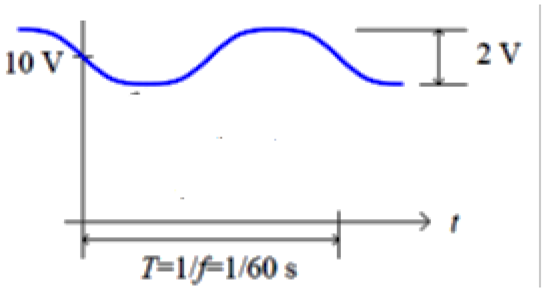
r_d represents the dynamic, AC or small signal resistance.

$$r_d = \frac{\eta V_T}{I}$$



Example: For the circuit shown below, determine v_d when $V = 10 + \cos\left(2\pi \times 60t\right)$ Volt. (Keith W. White – Lectures)





The diode specifications are

- *0.7 V drop and η = 2.*

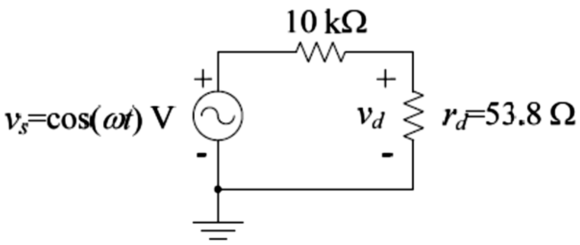
Solution:

DC Analysis:

$$I = \frac{10 - 0.7}{10{,}000} = 0.93 \text{ mA}$$

$$r_d = \frac{\eta V_T}{I} = \frac{2 \times 25 \times 10^{-3}}{0.93 \times 10^{-3}} = 53.8 \quad Ohm$$

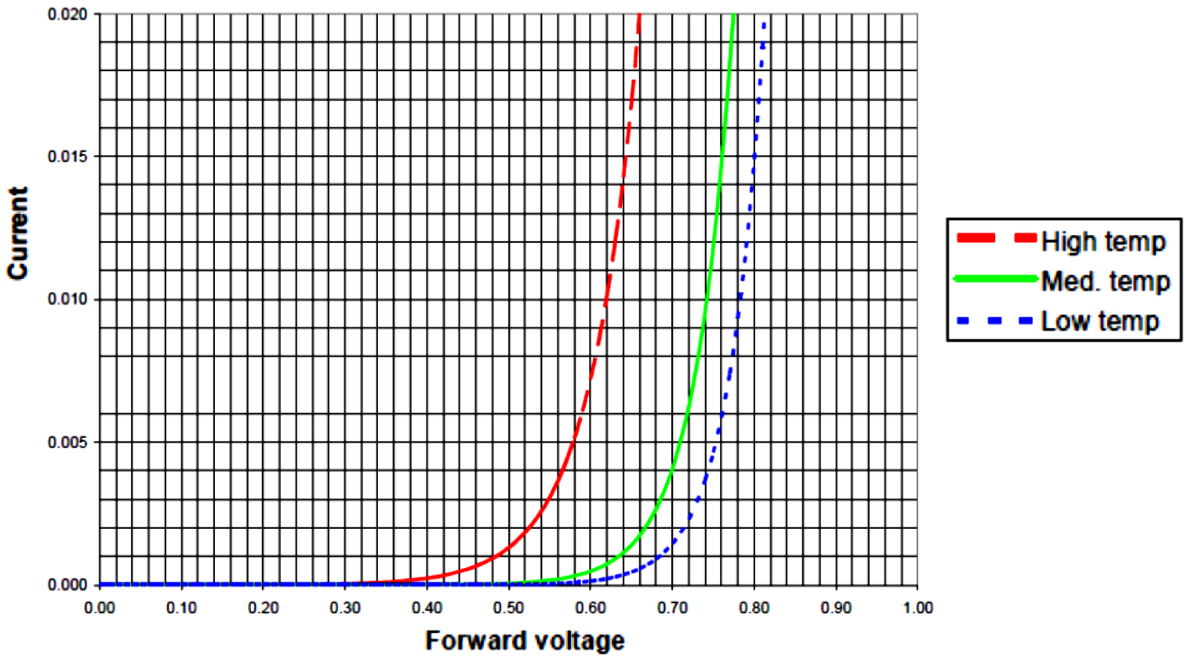
The AC equivalent circuit will be:



$$v_d(t) = \frac{r_d}{r_d + 10{,}000} v_s = \frac{53.8}{53.8 + 10{,}000} \cdot \cos(\omega t)$$
$$= 5.35 \cos(\omega t) \text{ mV}$$

1.4.5 *Effect of Temperature on Diodes*

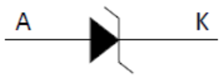
As temperature increases, more thermal energy is available to electrons enabling them to escape their binding atoms more eagerly. This causes the knee voltage (the voltage at which the diode turns on) to decrease.



1.5 Diodes Types

1.5.1 Zener Diode

- ***Zener Diodes*** are purposely designed to operate under ***reverse breakdown conditions***. It is heavily doped to reduce the breakdown voltage. This causes a very thin depletion region. As a result, an intense electric field exists within the depletion region. Near the Zener breakdown voltage (***VZ***), the field is intense enough to pull electrons from their valence bands and create current.



Schematic Symbol for a Zener Diode

The Zener model to be employed for the "on" state will be as shown in the figure-a shown below. For the "off" state as defined by a voltage less than V_Z but greater than 0 V with the polarity indicated in figure-b, the Zener equivalent is the open circuit that appears in the same figure

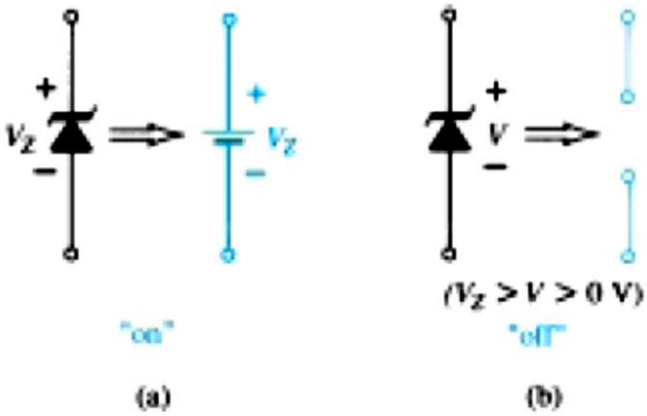


Figure a and b: Zener diode equivalents for the (a) "on" and (b) "off" states.

- **The main advantage of using Zener Diode in electronic circuits is to keep constant voltage across the load.**

The simplest Zener diode circuit appears in the figure shown below:

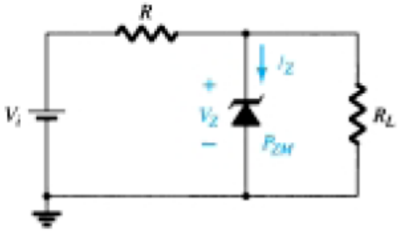


Figure: Basic Zener diode regulator.

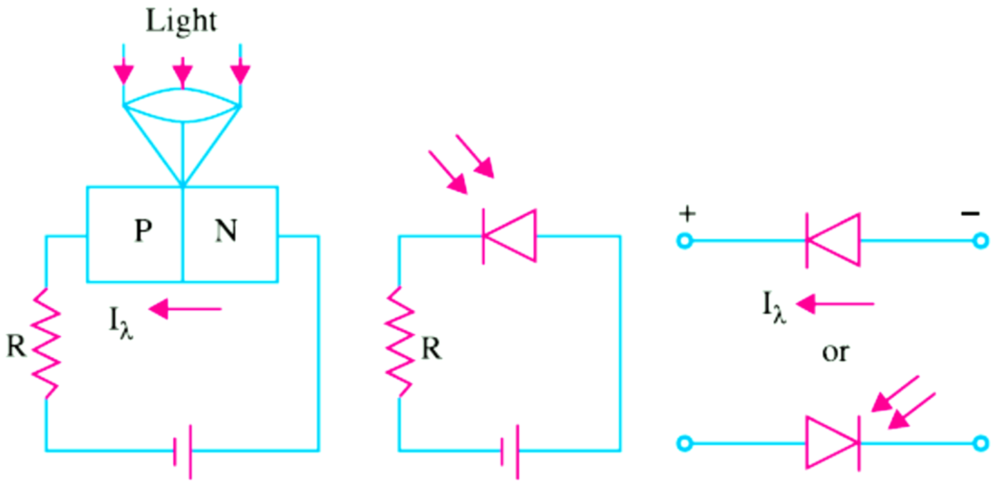
1.5.2 Schottky Diode

- Metal-semiconductor junction
- ~0.3V turn-on
- Often used in power applications
- Fast switching –no reverse recovery time

1.5.3 Light Sensors (Photo diode).

It is a two-terminal junction device which is operated by first reverse-biasing the junction and then illuminating it. A reverse-biased *P-N* junction has a small amount of reverse saturation current I_s (or I_0) due to thermally-generated electron-hole pairs. In silicon, *Is* is the range of nanoamperes. The number of these minority carriers depends on the intensity of light incident on the junction. When the diode is in glass package, light can reach the junction and thus change the reverse current.

The basic biasing arrangement, construction and symbols of a photodiode are shown in the figure shown below. As seen, a lens has been used in the cap of the unit to focus maximum light on the reverse-biased junction.



1.5.4 Light Emitting diodes (LED)

LEDs are p-n junction devices constructed of gallium arsenide (GaAs), gallium arsenide phosphide (GaAsP), or gallium phosphide (GaP). Silicon and germanium are not suitable because those junctions produce heat and no appreciable IR (IR: Infra-Red light) or visible light. The junction in an LED is forward biased and when electrons cross the junction from the n- to the p-type material, the electron-hole recombination process produces some photons in the IR or visible light in a process called electroluminescence. An exposed semiconductor surface can then emit light.