LECTURE NOTES

ELECTRONICS I

FOR

ELECTRICAL ENGINEERING STUDENTS

COMPILED AND EDITED

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1 Electronic Materials and devices

Semiconductor materials constitute the main foundation of this course, however before we embark on detailed study of the semiconductor materials and their uses in electronic circuits; we need to consider, first, the atomic structures of solids and their respective conductivity's.

1.1 The atomic structure

One of the most widely used models which describe the structure and behavior of atoms is known as the **bohr model** . This model postulate the atom as a nucleus containing neutrons (neutral particles, i.e. having no charge)and protons(positively charged particles) with electrons (negatively charged = to the protons charge) orbiting around it , grouped in shell forms ,as shown in fig (1).

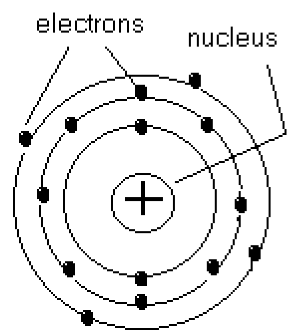


Fig 1 : The Atom structure

The weight of the electrons is almost negligible compared with the protons and neutrons ,i.e. **the weight of an atom (called the atomic weight)is roughly equals the combined weights of the protons and neutrons in that atom** , also **the number of element**(material) made of a particular types of atoms is described with what is called the atomic number of that element. **This is the number of electrons (or protons) orbiting the nucleus**. In general the structure of an atom is analogous to our solar system except in the case of atoms , electrostatic forces are exerted on electrons to hold them in place while in the solar system , gravitational forces are exerted on the planets orbiting the sun .

1.2 Atoms energy levels

1.2.1 The case of an isolated atom

For each atom their exist only a number of orbits(discrete energy levels) at which electrons may exist , **with no two electrons existing at any one energy level** . This is called the **Pauli's exclusion principle** .**The further the electron away from the nucleus the higher it energy state**(in the forms of kinetic and potential energies) , **The unit of energy** which is adopted in atomic theories is called the **Electron volt(eV)** ,where 1eV= 1.6 X 10 -19J. The electron volt is the amount of energy gained or lost when an electron moves with or against a potential difference of one volt .
Returning to the atomic structure of atoms ,electrons could not have any value of Electron volts other than an allowable one .
For the purpose of chemical behavior , is it better to group the possible energy levels (or orbits) to what is called **electrons main shells** (denoted K, L, m ,N .... ,Z with the k-shell being the closest to the nucleus) as shown in fig (2).

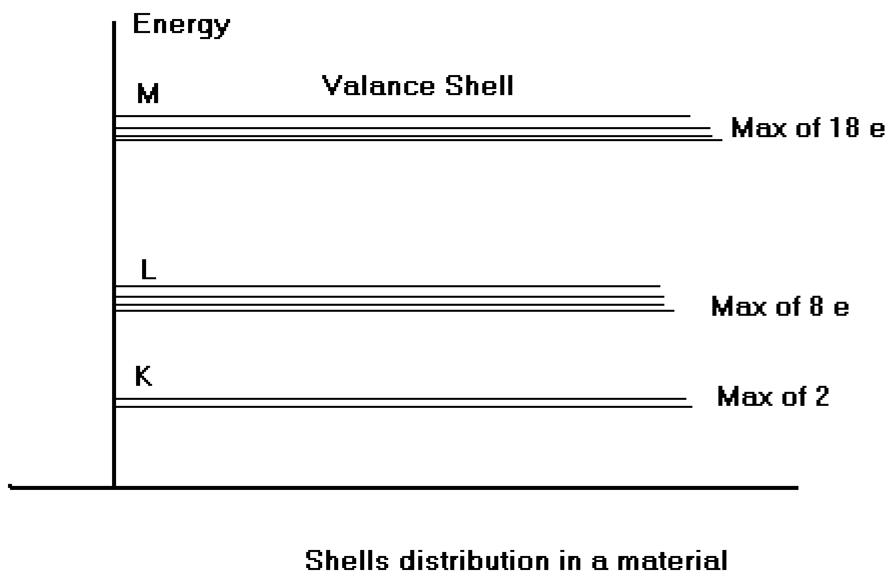


Fig 2 : Shell energy distribution for a material

with the number of electrons existing in the various shells determining the chemical behavior of the material. The first shell is considered complete when it contains two electrons and the second shell is complete when it contains eight electrons and the third shell is complete when it contains eighteen electrons and the fourth 32 and the fifth 50 etc. **($2n^2$)**.

Many of the chemical and electrical properties of materials are determined by the electrons existing in the outer shell (called the Valance electrons) , for example when an outer shell is complete , the material belongs to an inert gas .It should be pointed out at this stage that an electron existing in a shell further away from the nucleus(e.g. a valance electron) have a higher energy and thus may be detached from it's respective shell quite easier than electrons existing in inner shells .This can be done by increasing the energy of the electron by a specified level called quantum energy (e.g. in the form of heat or light) .which causes it to break away from it's shell . Similarly, decreasing the energy of a particular electron causes it to move to a closer shell to the nucleus.

1.2.2 The case of combination of atoms - in solids

When atoms of the same **material are brought together** , the atoms bonds (each atom attempts to have eight electrons in it's outer shell) with each other electrostatically by means of one of three possible methods :
(a) **Ionic bonding forces** -- Valence electrons join with other valence electrons to fill the latter outer shell
(b) **Covalent bonding forces** -- Valance electrons are shared between more than one atoms
(c) **Metallic binding forces** -- Electron cloud (wondering electrons) exert electrostatic forces on the positive Ions and hold them together (e.g. CU material) .

In this course only covalent bonding will be considered, since it is most applicable to semiconductor material .
When atoms are bonded together , their respective discrete energy levels are modified to become what is called **energy band** . within each band there are still discrete permissible energy levels rather than a continuum level . The energy bands closer to the nucleus have less width compared with outer bands , this is because electrons associated with inner shells interacts less with each other , while Valence electrons have strong interaction with each other resulting in higher modifications to their respective energy levels . for this reason only **the valence band will be considered in the study of the conduction properties of solid materials .** The highest energy band associated with atoms which are brought together (solids) is called the valence band (Fig 3) , since it contains the valence electrons . above the valence band their exist what is called the **Conduction Band where electrons in this band are not attached to any**

atoms and are free to wonder about and be influenced by external forces . Between the valence band and conduction band their exist a region called the **Forbidden band** where electrons can not exist .

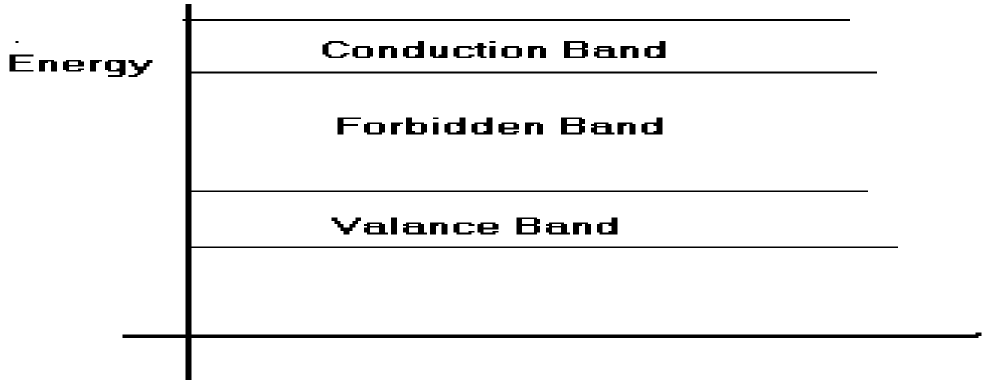


Fig 3 , Energy Bands in a Material

1.3 **Classifications of solids in term of their conductivity**

Electric current can be defined as the movement of charges , thus the ability for electrons to move from the valence band to the conduction band determine it's conductivity . it follows that there are only three main types of materials to consider :

A conductor -- at room temperature , **the valance and the conduction bands overlap each other** making it easy for a valance electron to reach the conduction band (Fig 4)

An insulator -- at room temperature, **the forbidden band is so wide** that valance electrons without the application of external forces , can not reach the conduction band

A semi-conductor-- at room temperature , their exist **a forbidden band with width some where between zero (conductor) and very wide (isolator)** so that without the application of external force some electrons (only few) find their way to the conduction band , and raising the temperature of the material causes the release of more electrons (negative carriers) from the valence band , effectively increasing the conductivity of material (opposite to most solids)

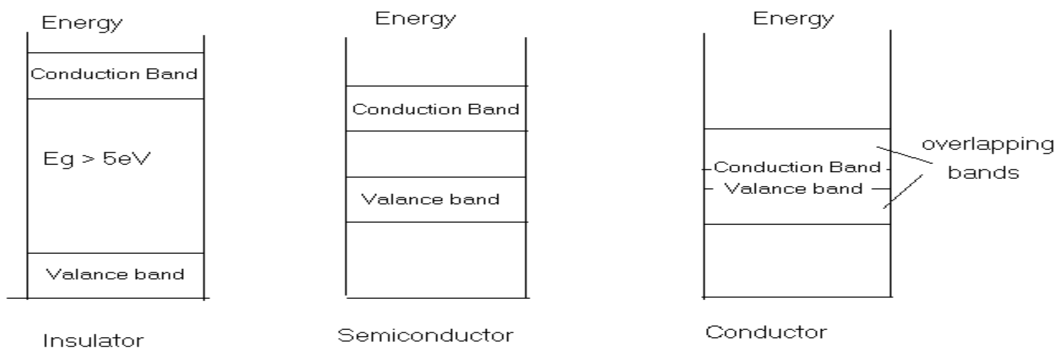


Fig 4 : Classifications of Materials in terms of their conductivities

In terms of electrical terms , the conductivity of semiconductor material (p = RA/l ohm.cm , R is the resistance of the conductor , A is the cross-sectional area of the conductor and L is it's length) **lies somewhere between that of an insulator and conductor**

1.4 Semiconductor materials

The most widely used semiconductor base materials , in the manufacturing of electronic devices are called **Silicon and germanium** (**four electrons in the outer shell** -- each has four valance electrons) ,with the germanium material having a conductivity at room temperature .

1.4.1 The N -Type semiconductor material

On it's own , The atoms of semiconductor material (pure state) , say **Silicon atoms , forms a strong crystalline structure (covalent bonding) with each other** (Fig 5)

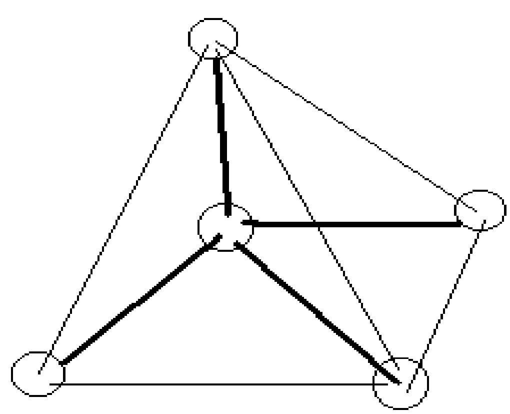


Fig 5 : The covalent crystalline structure of silicon atoms

, i.e. valance electrons of atoms are shared in order to complete the outer shells of atoms . In this state , and as mentioned earlier , and at room temperature , only some electrons , **due to manufacturing problems** , , from the valance band manage to escape such bonds , to the conduction band ,creating some vacancies (holes) and resulting in some (very small) current flow in the material . The material , in this case is called **intrinsic material .**

The conductivity of such material can be enhanced quite considerably by adding **(1 part to a 1 millions)** to the semiconductor material some impurities of other material (such as **arsenic or phosphor**) **which has five valance electrons** .For each atom of impurity material only four of the five electron can form a strong bond with the silicon atoms as shown in fig (6) , leaving one electron

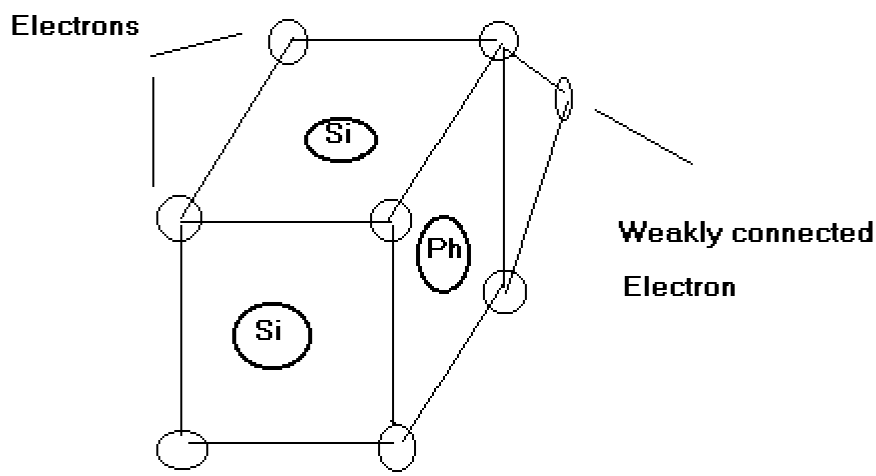


Fig 6 : Covalent structure of Silicon and Phosphor

loosely bonded .Effectively, the forbidden band is reduced , making it easier to initiate electrons flow with minimum applied energy . **The composite material** , in this case **is called Extrinsic material** and the impurity material is called **donor atoms ,or donor ions** (**since it donates electrons to the silicon material**) and the **electrons** , in general , forms **the majority carrier** .it should be pointed out that the number of holes has not changed significantly from the intrinsic state , for this reason the **holes are called the minority carriers .**

1.4.2 The P-Type semiconductor material

Adding , **impurity material**s with **three valence electrons** (boron) results in a material that has many vacancies (holes) for electrons (net positive charge) as shown in fig(7) . The composite material is now **called , P-type extrinsic material** , and the **impurity material** is **called acceptor atoms**, or acceptor ions (since it accepts electrons) and positive charges forms the majority carriers , whereas the **small number of free electrons existing in the material is called Minority carriers**.

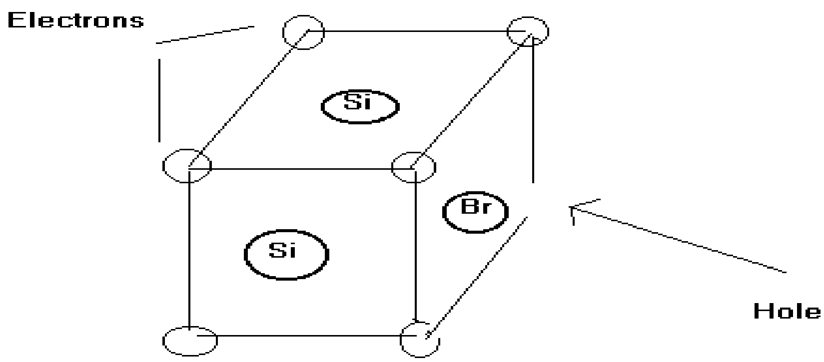


Fig 7 Covalent structure of Silicon and Boron

1.4.3 Current flow in semiconductor materials

The current flow in semiconductor material can be achieved in one of two ways :

(a) Drift current

As the name implies , the current flow is produced **when a potential difference is applied across the material** , which causes a general drift of electrons erratically (due to collisions encountered with other atoms) through the material towards the higher potential side (the positive end) Fig 8 .

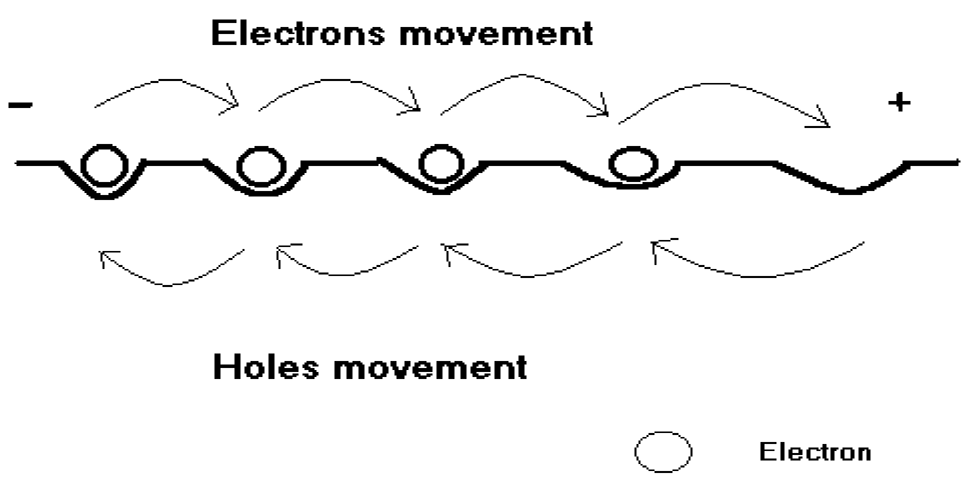


Fig 8 : Drift Current as a result of applying external energy

(b) Diffusion current

Such a current is produced when (**without the application of external energy**) a concentration of carriers is introduced to the material (just as adding a drop of ink to a glass of water) . The concentration of charges in one part of the material causes (due to a potential gradient) the charges in the higher concentration areas to move (diffuse) towards the lower concentration area, producing the diffusion current

1.5 Semiconductor device - The PN Junction

Recall that an N-Type material has electron majority (positive ions) and holes minority while the P-Type material has holes majority (negative ions)and electrons minority .

When the two materials are brought together , as shown in fig (9) , and at room temperature , **some of the electrons form the N Type material migrate (diffuse) into the P-Type material across the dividing line (Junction) neutralizing atoms in the P region near the junction**.

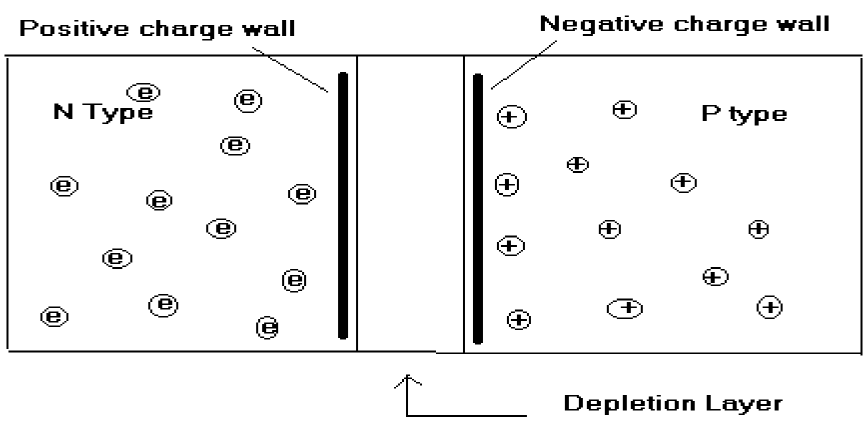


Fig 9 : The Depletion layer created as a result of and N and P layers are brought together

Similarly ,**some of the holes (positive charges) migrate from the P-Type material to the N-Type material neutralizing atoms in the N region near the junction** .As the N_region near the junction looses electrons ,the number of positive ions increases in that region until a stage where the repelling electrostatic forces between the positive ions and the incoming (from the P-Type material) holes acts to stop the migration of the holes . Similarly , as the P-region near the junction looses holes , the number of negative ions increase in that region up to a stage where repelling electrostatic forces between the negative ions and the incoming electrons acts to stop any further migration of electrons across the junction . i.e. **an area is created near the junction which has no charge carriers**. This is **called the depletion layer** .**The energy associated with the depletion layer form a barrier** (equivalent to a small potential difference , 0.3v for germanium material and 0.7 v for silicon material) , any electron or hole has to gather an energy level above that of the barrier to make the jump across the junction .It should be pointed out at this stage that a diffusion currents is produced(due to the existence of minority carriers) in the N and P layers , however , the net resultant diffusion currents equals to zero .

1.5.1 The basic connections of the Junction diode .

There are two basic connections for the diode :

(a) The reversed biased connections

Fig (10) shows the reversed bias connection , The positive terminal of the battery attracts the electrons (the majority carriers) in the N-Type material and the negative battery terminal attracts the holes (also the majority carriers) from the P-Type material , effectively widening the energy barrier and making it extremely hard for an electron or a hole to make a jump across the junction . i.e. there is no current flow

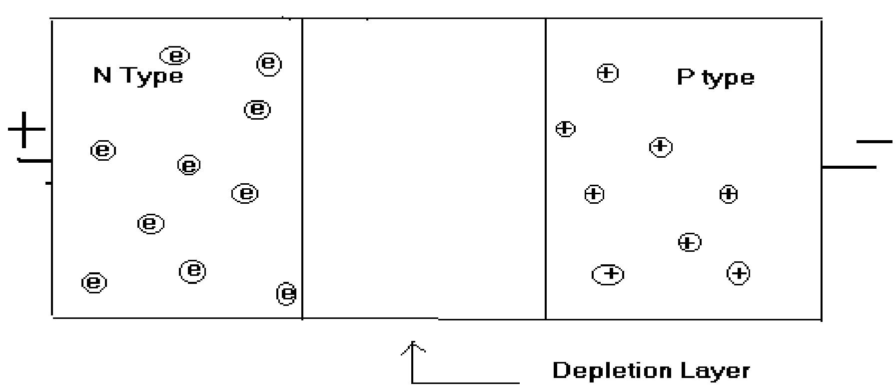


Fig 10 : Reversed Biased Connection for the J Diode

across the junction due to the majority carriers .However , some very small current will flow due to the presence of minority carriers in both N and P Types materials . This current is of the order of few Nanoamps for silicon material and few Microamps for Germanium material , and in both types of materials the current stays constant (limited numbers of minority carriers) as the applied voltage is increased up to a stage , called break down voltage , which will be dealt with later ,the reverse current , suddenly , increases .

(b) Forward biased connection

Fig (11) shows the forward biased connection for the

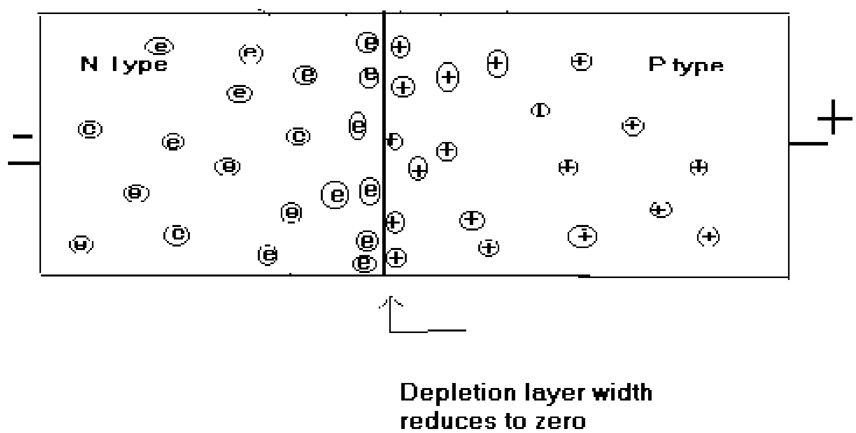


Fig 11 The forward biased connection of the J Diode

junction diode . The positive and negative terminals of the battery causes the electrons (of the N-Type material) and holes (of the P-Type material) to move towards each others , effectively reducing the energy barrier and causing a large current flow across the junction .The higher the applied voltage , the larger the current flow across the junction (majority carriers increases) .

Fig 12 shows the current / applied voltage relationship for the junction diode. Mathematically, the net forward diode current can be represented by the following equation:

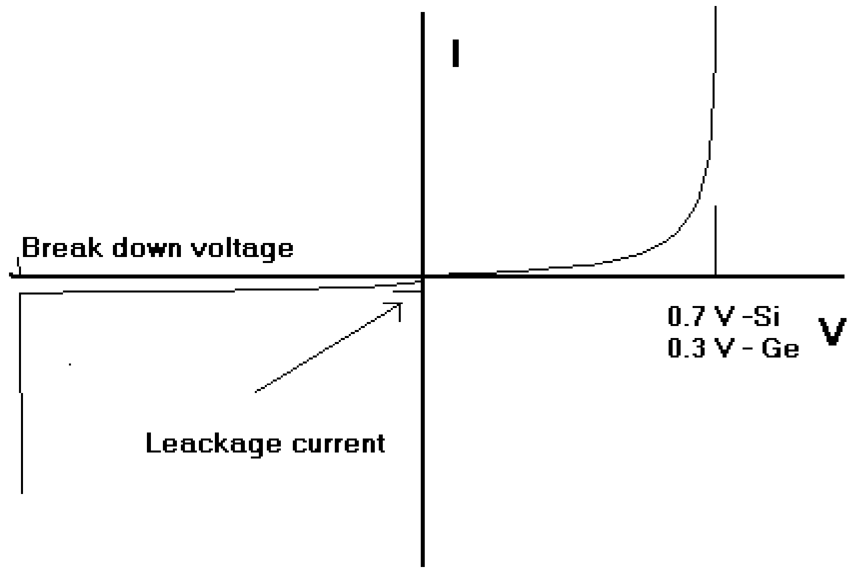


Fig 12 the current / applied voltage relationship for a J Diode

$$I_D = I_S\, e^{VD/nVT} - 1 \quad .... \quad 1.1`$$

where VT is a volt-equivalent of temperature and is equals to kT/q , k is a constant = 1.38 X 10 -23 J/K , T is the temperature in Kelvin's and q is the charge of electron = 1.6 X 10 -19 C .n is a constant between 1 and 2 (for this course this constant is taken to be 1).

1.6 Effect of temperature on the operational characteristics of the diode.

In general , increasing **the temperature of semiconductor materials causes the generation of more electrons/ holes pairs (minority carriers)** , thus in the diode , the increased electron/hole pairs acts to reduce the depletion layer width and subsequently reduce the forward voltage needed to produce a given forward current value .The increased minority carriers also causes an increase in the reverse leakage current as well as an increase in the avalanche breakdown voltage of the diode . Fig (13) illustrate the effect of temperature on the I - V relationship.

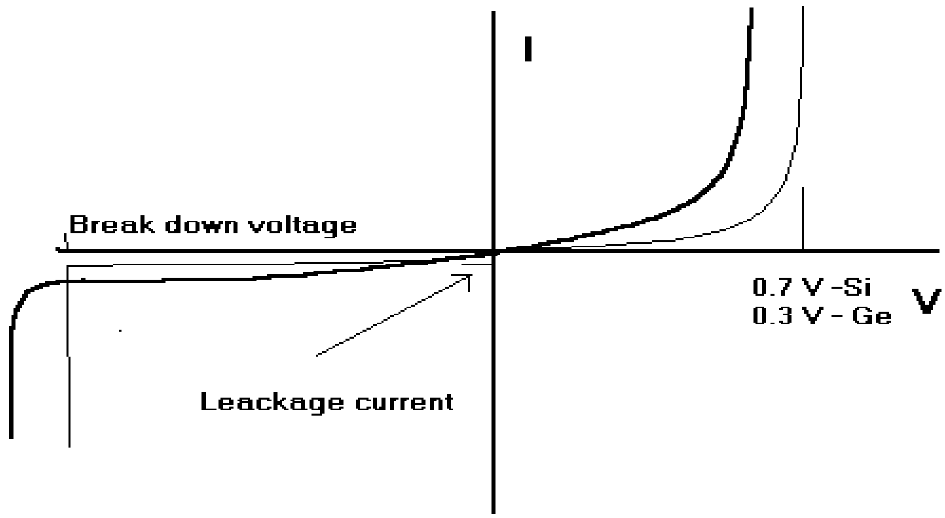


Fig 13 : Effect of increasing the temperature of the diode (the Dark curve)

1.7 Diode capacitance.

The space charged region (depletion layer) acts as an insulator in ordinary capacitance (potential difference across it) . As the diode is reversed biased, the depletion layer is widened and capacitance (called transition or depletion capacitance) is decreased. Similarly , when the diode is forward biased the depletion layer is reduced causing an increase in the capacitance (called the diffusion capacitance)as shown in fig (14).Special diodes exploiting the reverse biased capacitance effect are manufactured and used in modulation circuits (e.g. Varactor or varcap , which is in fact a diode with variable capacitance proportional to the reverse voltage Such a device, can be used in parallel with an inductor to provide a resonant tuned frequency proportional to V reverse , V reverse could be a voice signal , I .e. the frequency (resonant) will be modulated by the voice signal , as in FM systems .

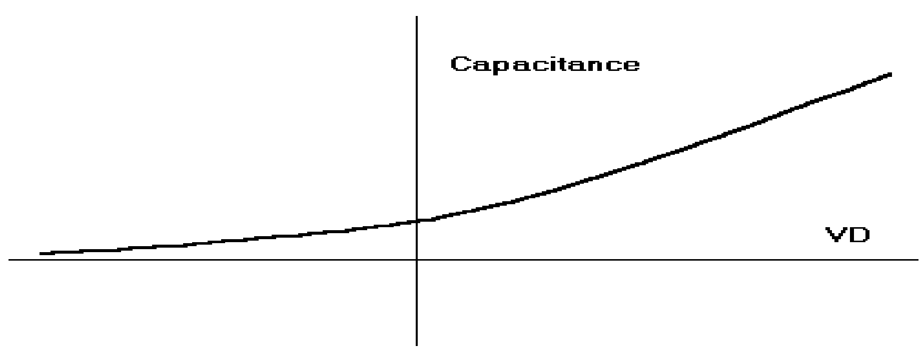


Fig 14 : The variation of Capacitance for a Diode

2 . Diode Circuits Analysis

2.1 The D.C Resistance of a diode

For a given diode the D.C (static) resistance R_{dc} is written as :

$$R_{dc} = V_D/I_D \quad ..... \; 2.1$$

Thus for the following characteristic, Fig (15), R_{dc} at V_D=0.8 is given by;

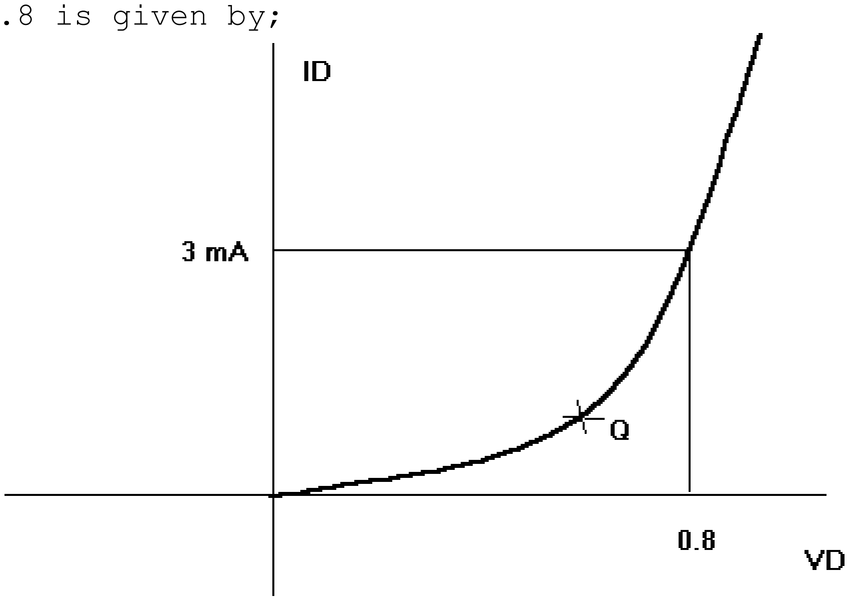


Fig 15

$$R_{dc} = 0.8v / 3 \text{ mA} = 266 \text{ ohms}$$

In general, the DC resistance of the diode in the reverse direction is very large (typically 5 M ohms) while the DC resistance of the diode in the forward direction is relatively low (typically 200 ohms).

2.2 The AC diode resistance

Because of the nature of varying signal (AC) the AC resistance of the diode can be evaluated as follows :

(a) For small signals (small variations) the AC resistance of the diode is given by:

$$R_{ac} = \text{delta } V_D / \text{delta } I_D \quad ....2.2$$

evaluated at operating point Q , as shown in Fig (15) , a value for Equation 2.2 can be derived from equation 1.1 as follows:

VD/VT

$$I_D = I_S\, e^{V_D/V_T} - 1 \quad , \text{ for } n=1$$

$$I_D \cong I_S\, e^{V_D/V_T}$$

$$d I_D / d V_D = I_S / V_T\, e^{V_D/V_T}$$

$$\cong I_D / V_T$$

R_{ac} = delta V_D / delta I_D , at Q point

= V_T/I_D , at Q point 2.3

at room temperature , 25 degrees , V_T = 26 mV

i.e. at room temperature R_{ac} = 25 mV / I_D , at Q point

and taking into account the contact resistance (of the external wires to the semiconductor materials RB , it follows that the AC resistance of the diode may be written as :

R_{ac}= 25 mV/$I_{D\ ,Q\ point}$ + R_B 2.4

(b) for large signal level
The Ac resistance of the diode under this situation (called here the average resistance) can be simply calculated from the V/I characteristics of the diode as follows :

R average = the max - min values of VD / max-min value of ID 2.5

2.3 The diode equivalent circuit

In the following approach, the diode characteristics may be simplified as shown in Fig (16-a, 16-B, 16-C). This approach is

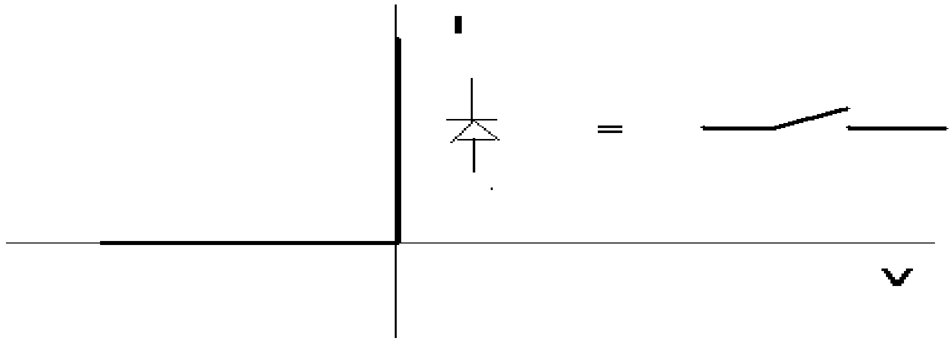


Fig 16 –a : The Diode as a simple switch

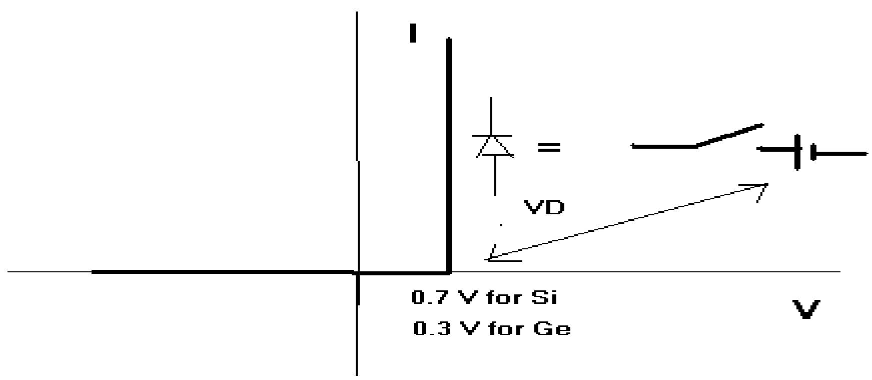


Fig 16-b : taking into account the forward voltage for the diode

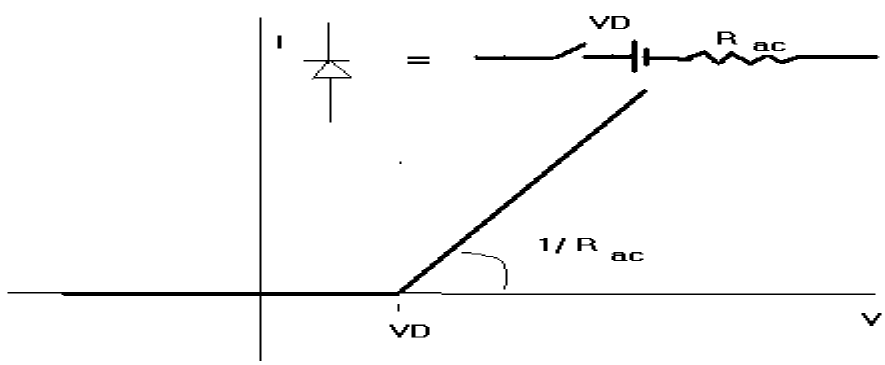


Fig 16-c : taking into account the internal AC resistance for the diode

called the **Piecewise linear equivalent circuit** . and may be explained as follows :

The silicon diode requires approximately 0.7 V (0.2 –0.3 V for germanium diode) of forward voltage before it starts to conduct and, once it does conduct the current (forward) is limited by the diode AC resistance (Dynamic resistance

).The inclusion of the diode in the equivalent circuit is to illustrate the direction of flow of current only (Fig 16 –c) .
Further simplification to the method considers the dynamic resistance of the diode to be zero as shown in Fig 16 –b . Also in large forward voltage applications the 0.7V required to fire the diode may be neglected as shown in Fig 16-a , i.e. the diode may be represented as a switch.

2.4 Power dissipation in P-N diodes

The power dissipation of the diode is simply calculated from the following equation:

The power of the diode PD = V_D X I_D 2.5

Where V_D and I_D are the current through the diode and the voltage across it.

However , the power P_D is closely related to the junction temperature , that is , the higher the P_D , the higher the temperature of the junction of the diode and if the P_D is allowed to go above a specified level , the junction may be damaged permanently .Also , the junction temperature is influenced by the surrounding temperature, T_S .
The manufacturers specify a maximum junction temperature T_J which is given by the following equation :

T_J = T_S + Thermal Resistance X P_D 2.6

Where The thermal resistance is a constant specified by the manufacturers (units of C/mW)

2.5 Diode circuits and applications

2.5.1 Diode circuits

Recall that the ideal diode (negligible average resistance and negligible forward voltage) can be treated as a switch as follows (Fig 16-a), and that the inclusion of the forward diode voltage would modify the above representation as shown in fig 16-b, then we may perform a straight substitution for the diodes in electronic circuit and apply conventional circuit analysis methods to obtain various solutions.

.5.1.1 Example , Simple diode circuit

Referring to Fig 17,Since point A has a higher potential than point B , then the diode may be replaced by it's equivalent switch component as shown in Fig 16 –a , If the diode is reversed biased then it may be replaced by an open circuited switch ,i.e., the full voltage(input) will appear across the diode , as shown Fig 17

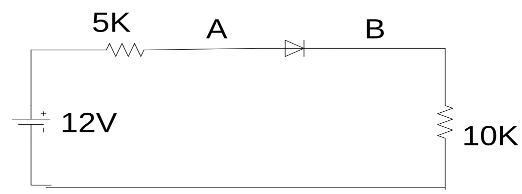


Fig 17 simple diode circuit

2.5.1.2 Example , Circuit containing double diodes

Referring to Fig 18 ,If one diode is reversed biased then that diode can be treated as an open switch and no current flow in the circuit .

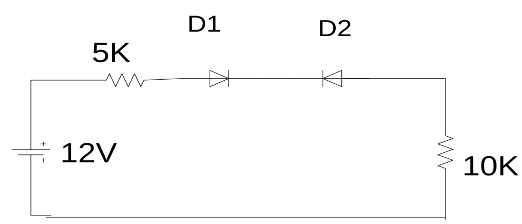


Fig 18 D1 is forward Biased and D2 is reversed Biased

2.5.1.3 Example : Multi source circuit

Referring to Fig 19 , we need to determine whether the diode is forward or reversed biased . One method is to remove the diode (replacing it with a short circuit) and solve the circuit to determine the direction of current flow in that short circuit and based on the result we may proceed to replace the diode with it's respective equivalent switch status (open or closed)

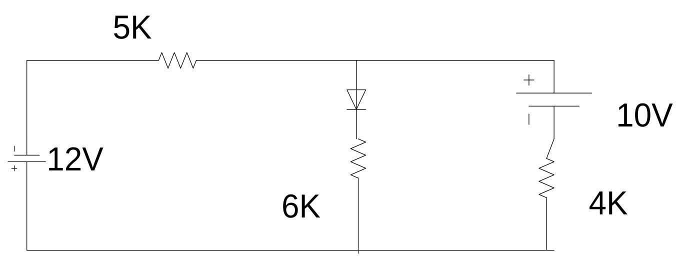


Fig 19 multi – source diode circuit

2.5.1.4 example : Parallel diode circuit

Referring to Fig 20 , again , replacing the diode with it's equivalent switch and applying conventional circuit analysis would yield the required results .

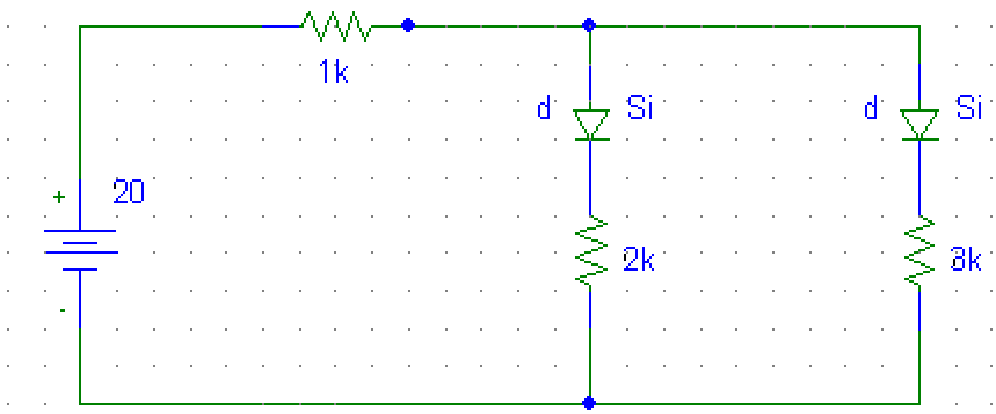
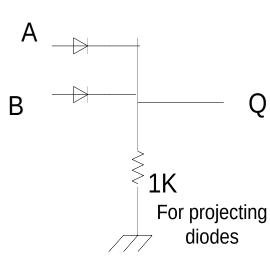


Fig 20 , Parallel diode circuit

2.5.1.5 Example : Digital circuit

Referring to Fig 21 , and replacing the diodes with their equivalent circuits yield the exact function of an "OR" gate



A	B	Q
0V	0V	0V
5V	0V	5V
0V	5V	5V
5V	5V	5V

Fig 21 ,Digital circuit implementation using diodes

2.5.1.6 Example : Relatively difficult diode status circuit

Referring to Fig 22 , it is not easy to determine the status of the diode by just looking at it , instead we need to perform circuit analysis (e.g. Thevinin or Kirchhoff) to determine potential levels across the diode and thus it's status .

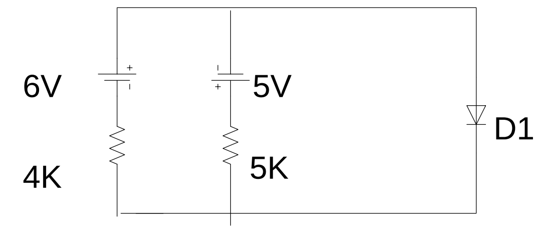


Fig 22 , Relatively difficult diode status circuit

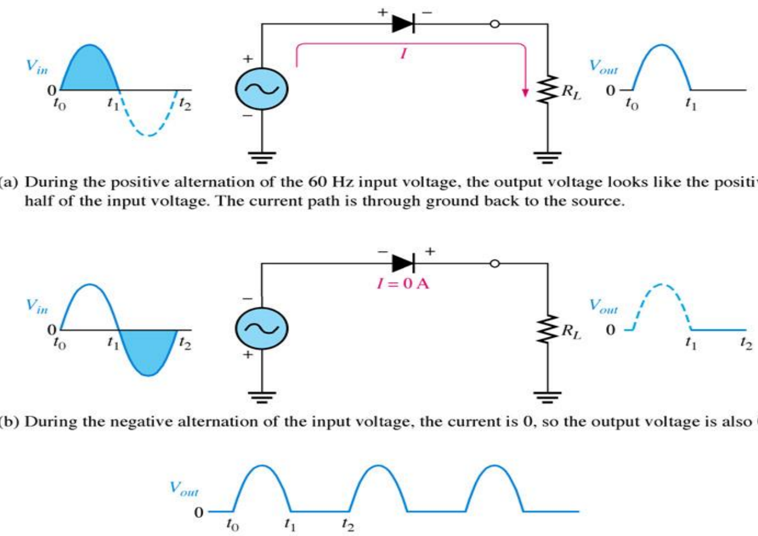
2.5.2 Diode applications

2.5.2.1 Rectifier circuits :

In general , a rectifier circuit , as the name implies , rectifies (iron out) the varying input signal and produces an output which has a DC component . Such a circuit is very important in power supply circuit designs where the AC signal is transformed to DC and thus made suitable as a supply for electronic circuits which function using DC only .In this section we will consider the half and full wave rectifier circuits .

(a) The halfwave rectifier :

consider the circuit given in Fig 23 ,and if $V_{in} = V_{max} \sin(wt)$,and assuming the diode to be ideal , then the output waveform will be as shown



(a) During the positive alternation of the 60 Hz input voltage, the output voltage looks like the positive half of the input voltage. The current path is through ground back to the source.

(b) During the negative alternation of the input voltage, the current is 0, so the output voltage is also 0.

(c) 60 Hz half-wave output voltage for three input cycles

Fig 23 , The Half wave rectifier circuit

The part of the waveform between 0 and 180 degrees has a mean value(DC or average)given by the following equation :

$$V_{mean} \cdot \pi = \int_{0}^{\pi} V_{max} \, Sin(wt) \cdot d(wt)$$

$$\text{i.e.} \quad V_{mean} = 0.637 \, V_{max}$$

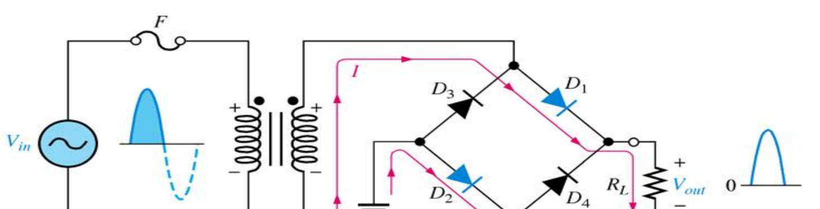
and for a full cycle , i.e. between 0 and 360 degrees ,and since the mean value for the part of the waveform between 180 and 360 degrees equals to zero , it follows that the mean value for the complete waveform equals :

$$(0.637+0) V_{max}/2 = 0.318 \, V_{max}$$

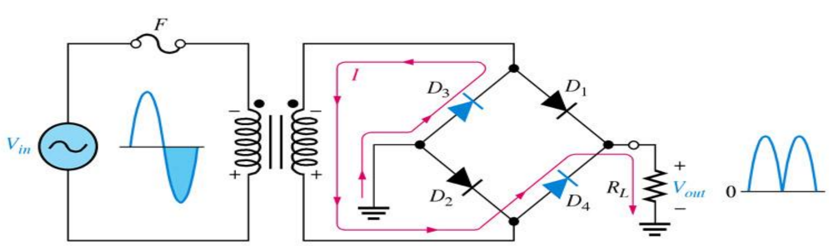
If the forward voltage for the diode V_T is taken into account ,then the output while the diode is conducting will be decreased by 0.7 V (0.2 for germanium)

(b) Full wave rectifier circuit

Using the circuit .in Fig 24 , and assuming that $V_{in} = V_{max} \sin (wt)$,then the positive half of Vin will find a path through the load and the negative half will also find a path through the load) although in the negative direction) , i.e. the output waveform will be of the form shown in the same Fig .



(a) During positive half-cycle of the input, D_1 and D_2 are forward-biased and conduct current. D_3 and D_4 are reverse-biased.



(b) During negative half-cycle of the input, D_3 and D_4 are forward-biased and conduct current. D_1 and D_2 are reverse-biased.

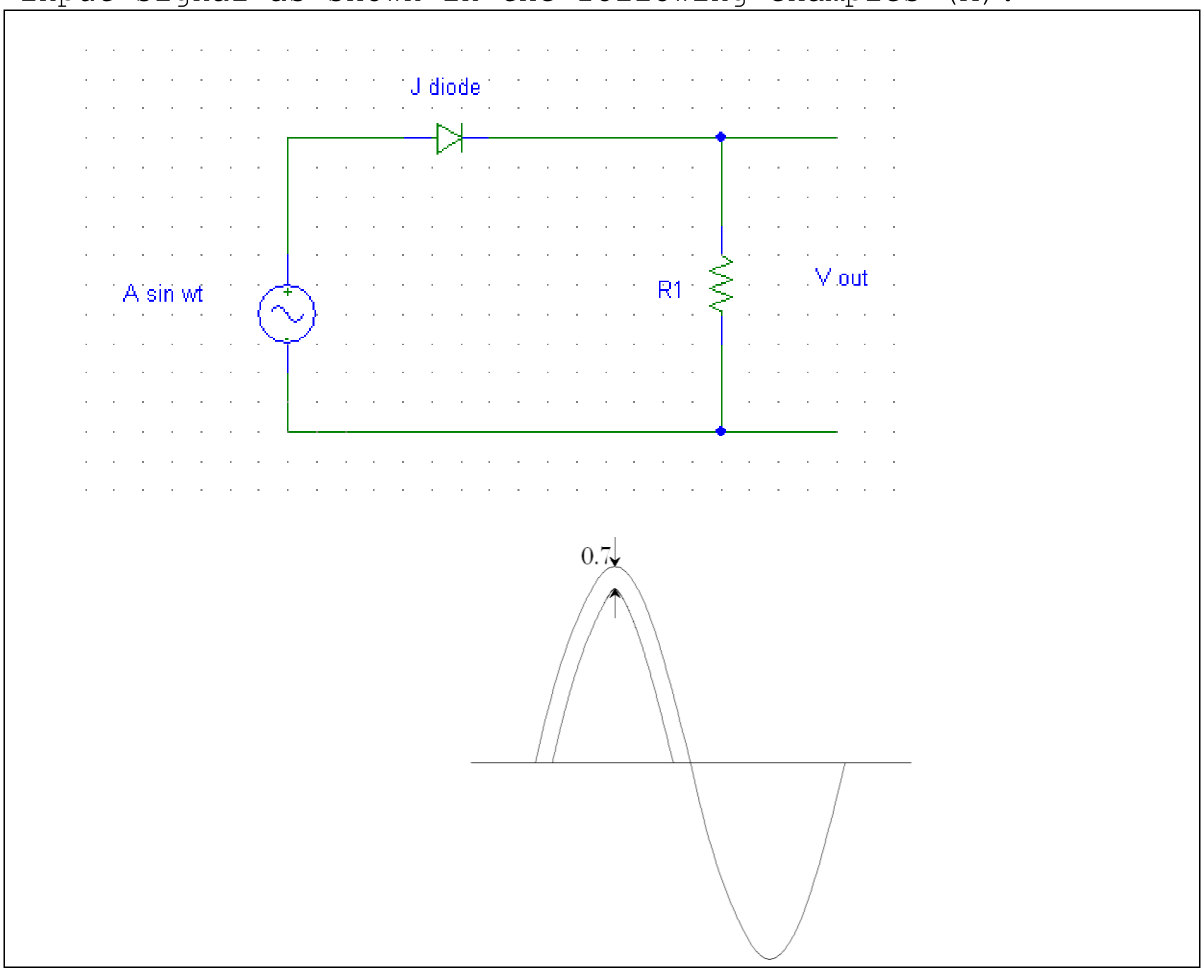
Using similar calculations to that adopted for the half wave rectifier circuit ;

$$V_{mean} = 0.638\ V_{max}$$

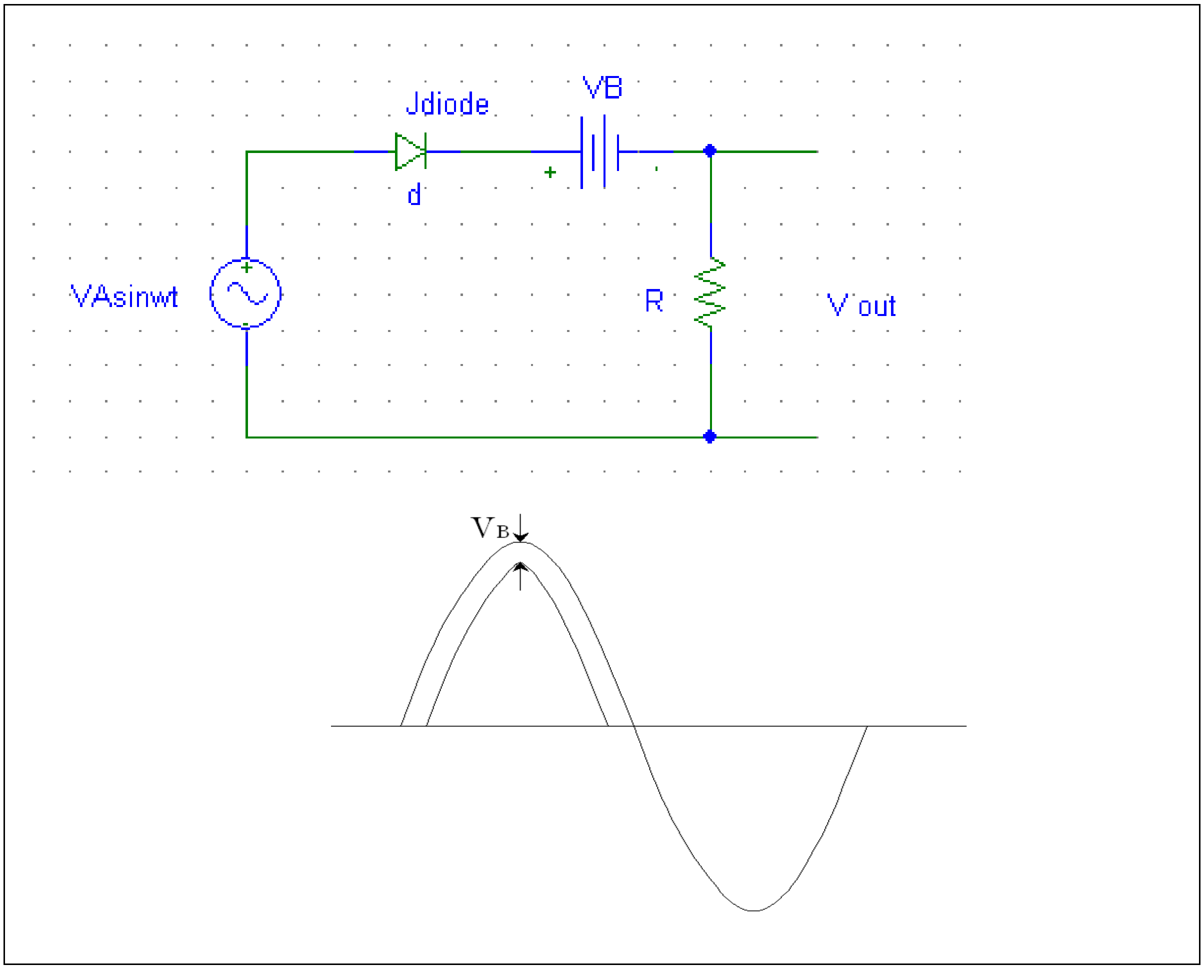
Since each half of the input signal passes through two diodes , then it follows that if V_T (forward voltage of the diode) is to be taken into account then the output swill be decreased by 2 X 0.7 V (for silicon).
It should be remembered that the break down voltage of the diode should be equal or more than V_{max} , otherwise the rectifier circuit will not function correctly .

2.5.2.2 Limiting (Clipping) Circuits .

Clipping circuits , acts to limit the input wave form (by clipping it) without affecting the remaining part of the input signal as shown in the following examples (A):

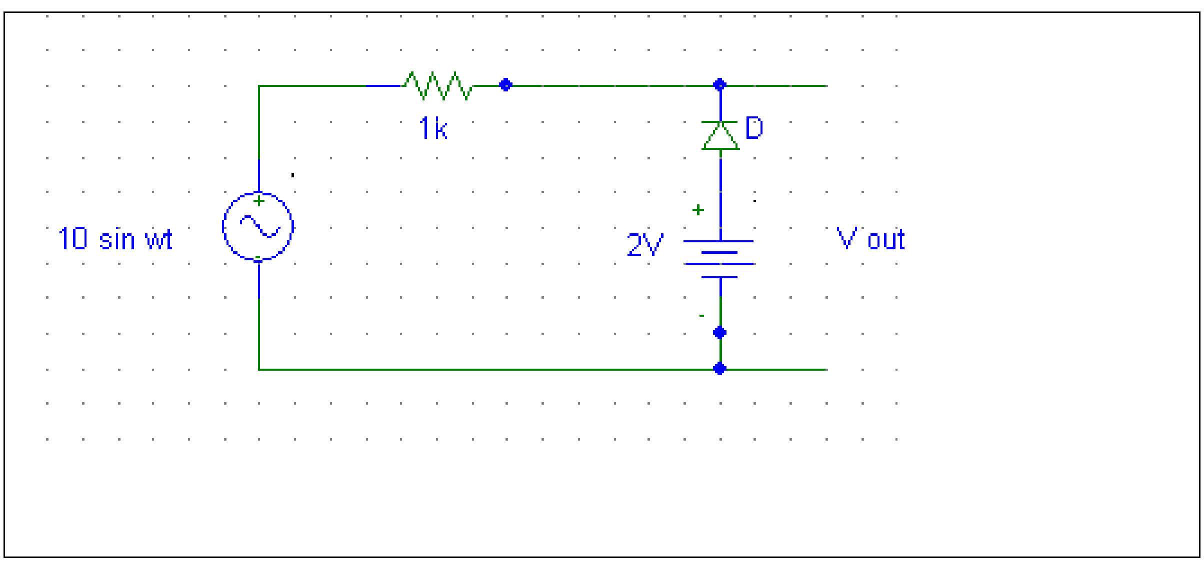


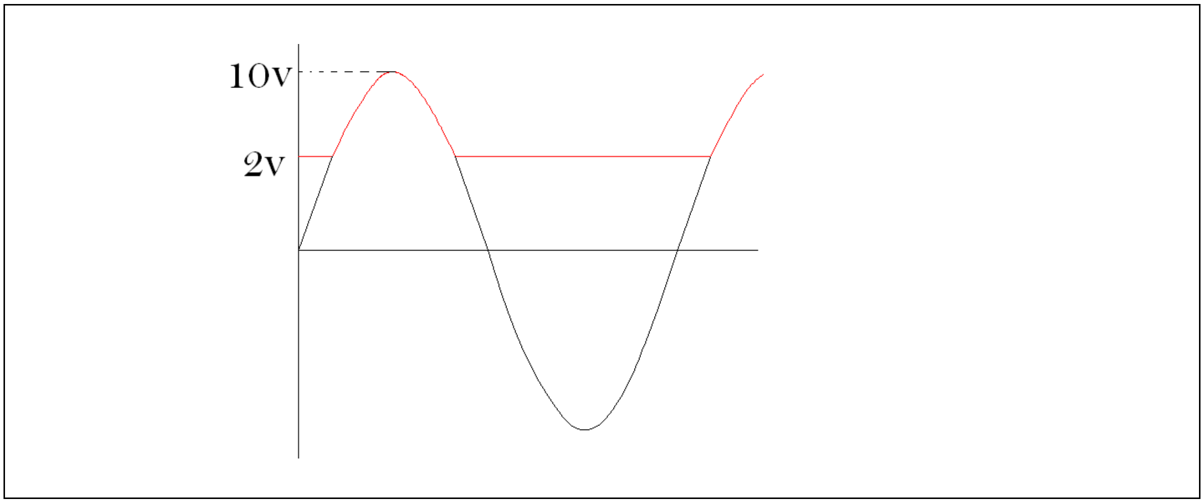
Example A
we treat this circuit as a half wave rectifier circuit , i.e. the negative part of the input signal is clipped



Example B

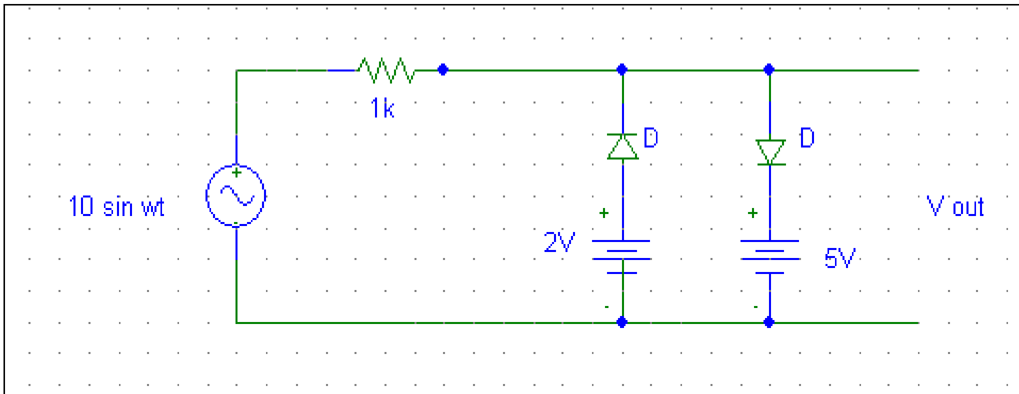
The inclusion of a voltage V_{dc} (example B)causes a decrease (or an increase based of the polarity of V_{dc}) in the output signal -- exactly in the same way as when the forward diode voltage V_T is taken into account in representing the diode.

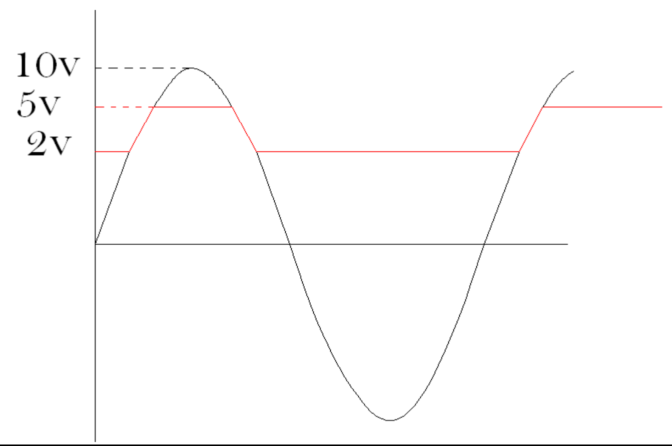




Example C

We analyze the response of the circuit point by point considering the diode as a switch





Example D

Each branch of the circuit can be analyzed separately to arrive to the output waveform .

2.5.2.3 Clampers Circuits

Clamper circuit as the name implies is a circuit which clamp (fix) an input signal to a d.c level . The circuit usually has a capacitor , to hold fixed voltages ,as well as a resistive element .Fig 25 shows a typical clamping circuit . The R and C values should be chosen so that a large time constant(given by 0.7 RC) is achieved , preventing the fast discharge of the capacitor . Ejecting an input signal of the form shown in Fig 25 yield a clamped output form as will be explained in the following paragraph:

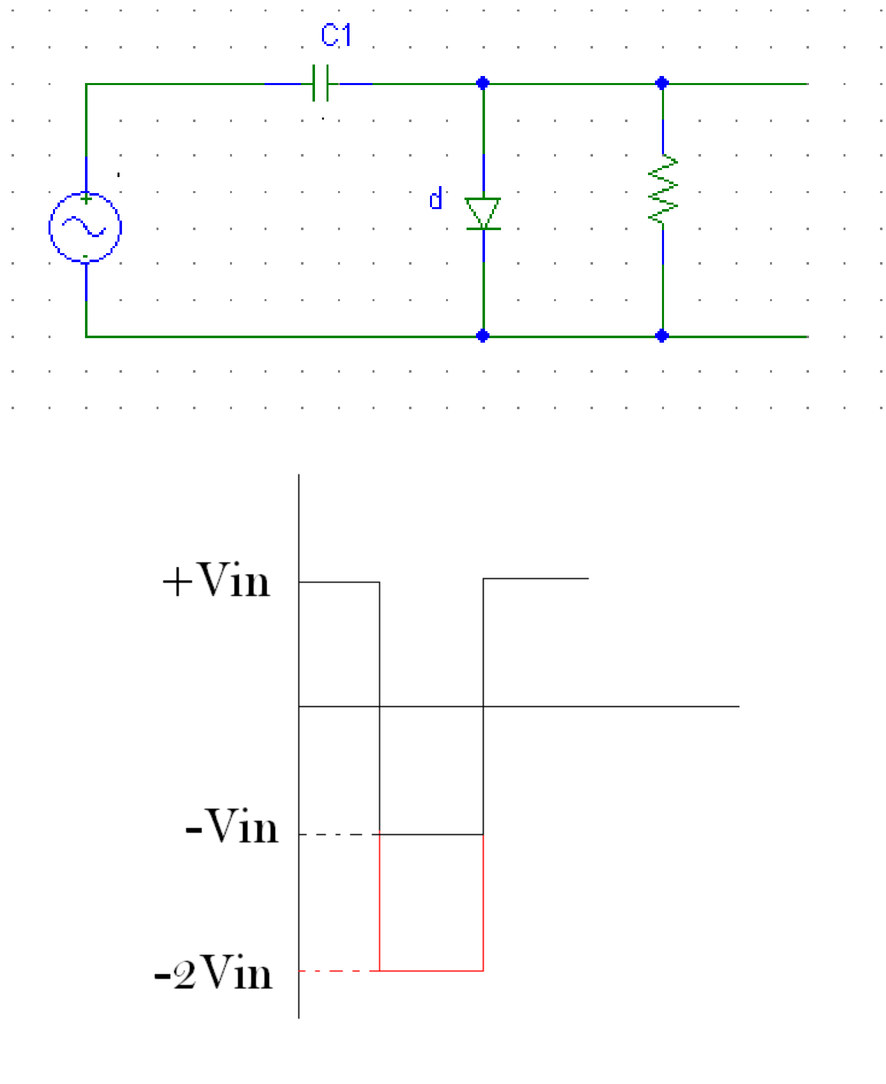


Fig 25 ; clamp circuit

(a) During the positive part of the input signal, the diode is treated as a short circuit and the capacitor charges up to the maximum value of the input signal.
(b) during the negative part of the input signal , the diode is treated as an open circuit and the resistive element experience DOUBLE (- V_{in} (held by the capacitor) - V_{in} (of the input signal) = -2V_{in}
The resulting output (across R) of the circuit is as shown in the same Fig .
It can be said that the output is clamped to zero level .

The general rules for analyzing the clamper circuit is as follows :

(a) Analyze the circuit when the diode is short circuit
(b) make sure that 0.7RC is much larger than the period of the input signal -- to prevent the rapid discharge of the capacitor .

2.6 Introduction to the concept of graphical analysis of electronic circuits .

2.6.1 The D.C Load Line

consider the following circuit ,Fig 26 , then using Kirchhoff Voltage Law , we may write the following equation :

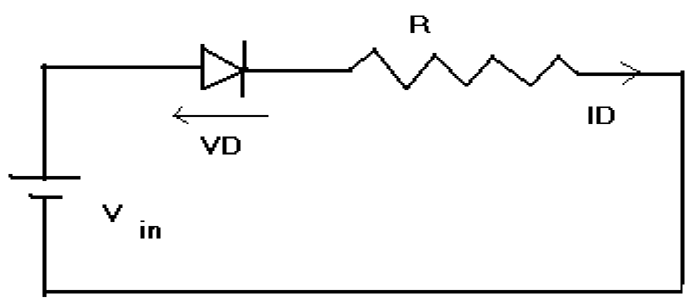


Fig 26

$$V_{in} = V_D + I_D.R$$

i.e.

$$V_D = V_i - I_D.R$$

the above equation is that of a straight line (with a slope of -1/R) which when plotted on the same axes as that for the V,I characteristic of the diode would yield an intersection point called the operating point Q , as shown in the Fig 27 :

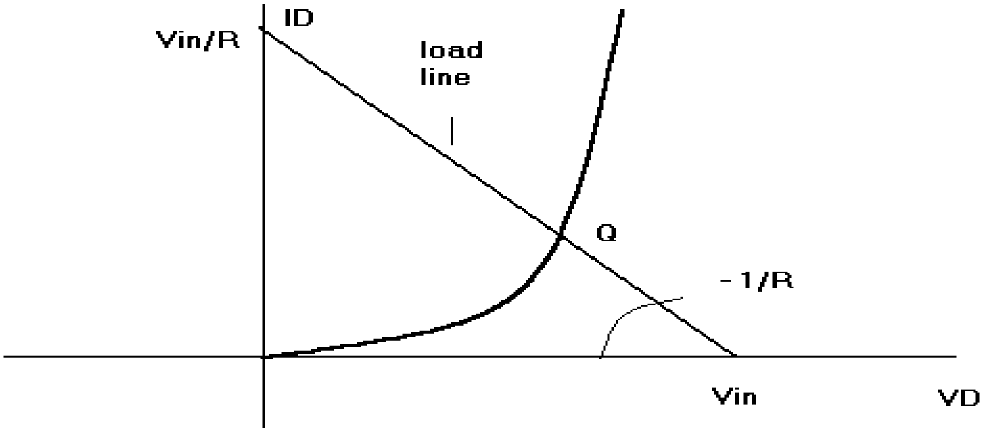


Fig 27 The DC load line

i.e. for the above circuit conditions , the values of V_{DQ} and I_{DQ} may be obtained directly from the above graph . Similar method may be adopted for the reversed biased case .

2.6.2 The dynamic Curve

It is clear that if Vin is varied then the load line will also vary accordingly as shown in Fig 28 . A plot of V_i against I_D yield what is called the dynamic characteristic of the diode

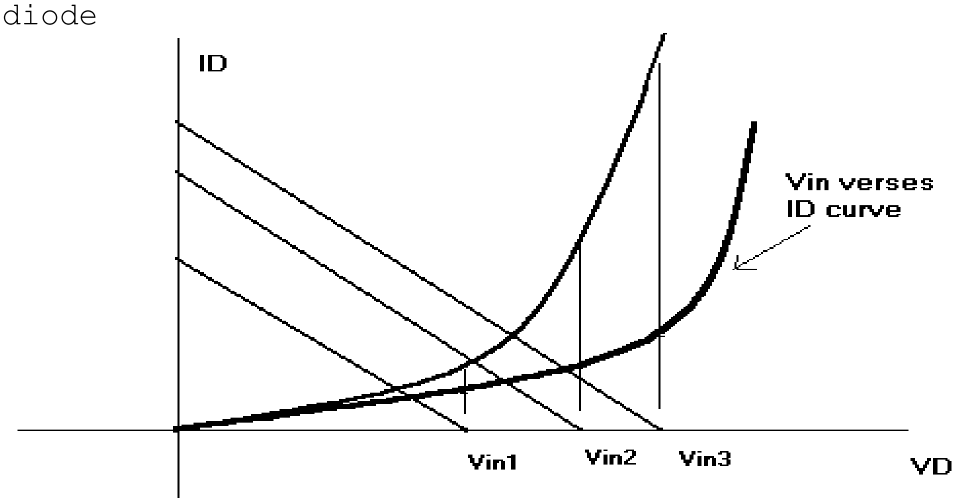


Fig 29 The dynamic Curve for the diode

2.6.3 The transfer curve

A plot of V_o (= I_D X R) against V_i yield what is called the transfer curve of the diode circuit , which has the same shape as the dynamic curve for the above circuit (resistive load) .

e.g. for the following circuit

then the output waveform (= I_D X R) can be deduced from the transfer curve as shown in the following diagram Fig 29 .

3 Special Diodes

3.1 Zener Diode

Referring to the standard Characteristic of an ordinary diode , and as the reversed applied voltage is increased , a stage is reached , where by the reverse diode current sharply increases . Such a voltage , and as mentioned in section 1.5.1 (a) , is called the breakdown voltage . The breakdown effect (low to high current)could be explained in term of The Avalanche breakdown (Minority carriers accelerated by the reversed voltage tends to knock other atoms and generate other electron / holes pairs) or the faster Zener Breakdown or both .The latter phenomena occurs at much lower voltage than that for the avalanche breakdown and is achieved as a result of doping the semiconductor materials with higher levels of impurities than ordinary diode which causes a marked reduction of the depletion layer and , consequently ,the ionization (creation of holes / electron pairs) of atoms by the electric field developing across the junction (electric field between two differing potential is inversely proportional to the distance between the points , and since the depletion layer is very thin then their exist a large electric field across the junction). Typical zener breakdown voltage is 5 Volts . Such a voltage may be varied by changing the doping levels of the N and P layers . Fig(30) shows a typical Zener diode characteristic curve .Once the Zener diode conduct, the maximum allowable current is limited by the power rating of the diode and the allowable junction temperature , similar to ordinary diodes .Also the Zener impedance(or resistance) can be calculated in similar manner to the conventional diode i.e. delta V/delta I

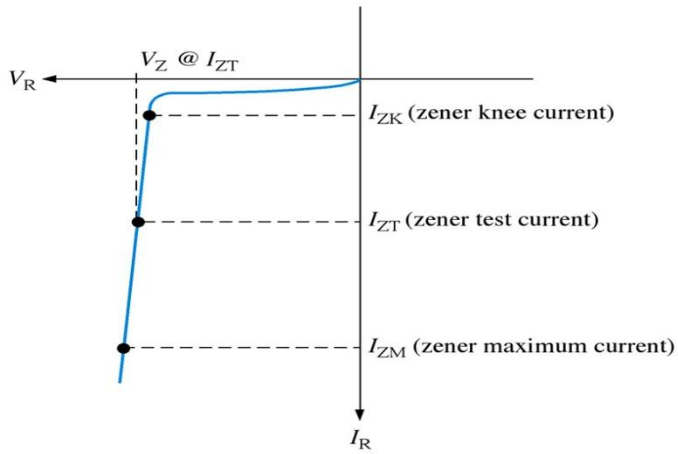
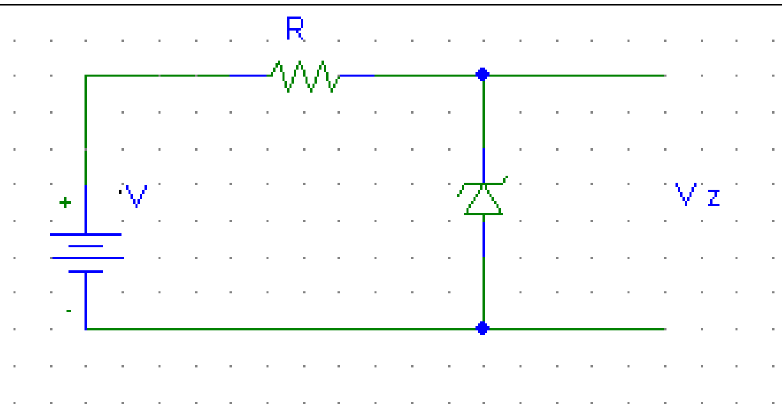


Fig 30 , the Zener Response

3.1.1 Zener diode as a circuit element

Analysis of circuits containing Zener diodes are performed in similar fashion to that for the ordinary diode i.e. approximate model and load line methods are applicable in this case .
consider the circuit of ,Fig 31 and applying kirchhoff voltage law around the circuit , for the zener part of the characteristic, yield the zener current. The zener impedance (or the dynamic zener resistance) can be calculated as follows



$$I_z = [V - V_z] / R$$

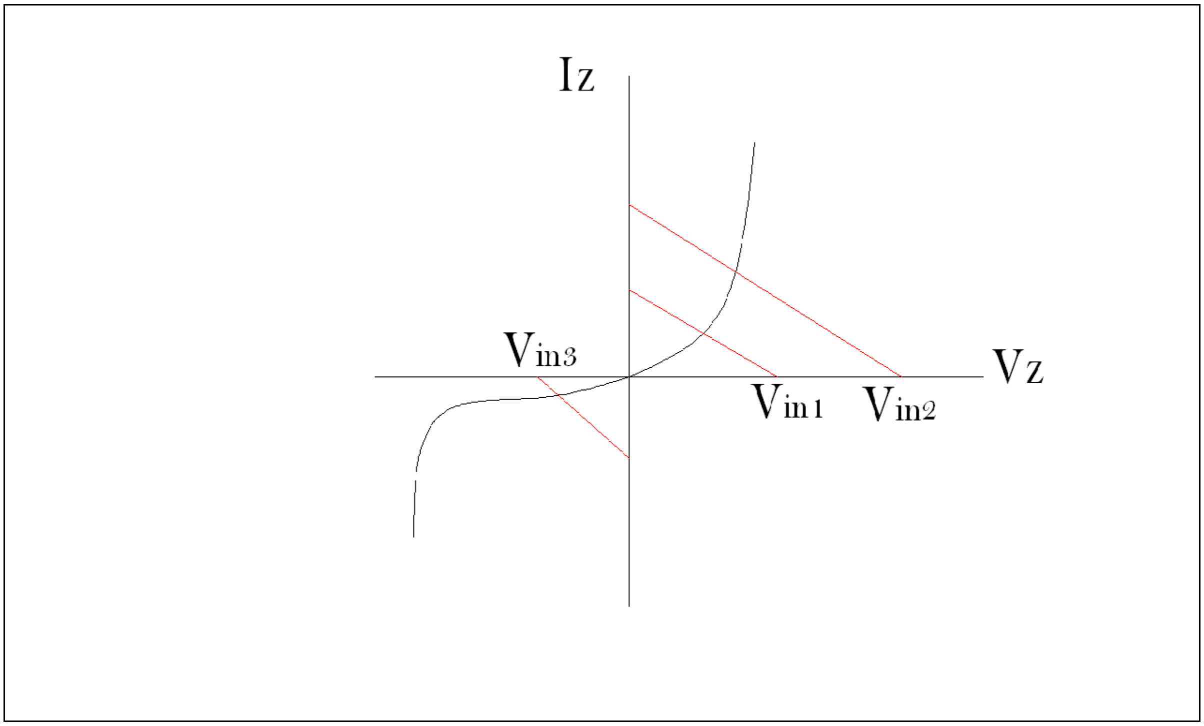


Fig 31 Simple Zener diode circuit

3.1.2 Zener diode applications

3.1.2.1 Voltage regulator

A voltage regulator circuit is a electronic network that regulate the voltage (keeps the voltage as constant as possible) supplied to the load . and to explain the principle of regulation consider the following example :

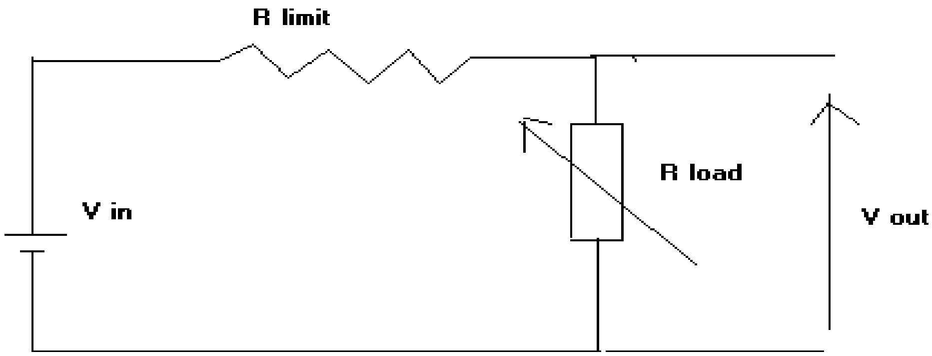


Fig 32

In the circuit of Fig (32) and if R_{load} is allowed to vary between it's maximum (infinity value -- open cct) and minimum values (zero value -- short circuit) the voltage across the load will vary between the following two limits :

Vout upper = V in

Vout lower = 0 V

i.e. no voltage regulation exist across the load .

if on the other hand a zener diode is introduced to the circuit as shown if Fig (33) and using the approximate

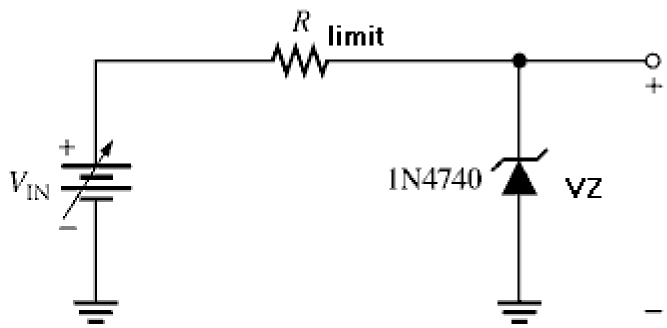
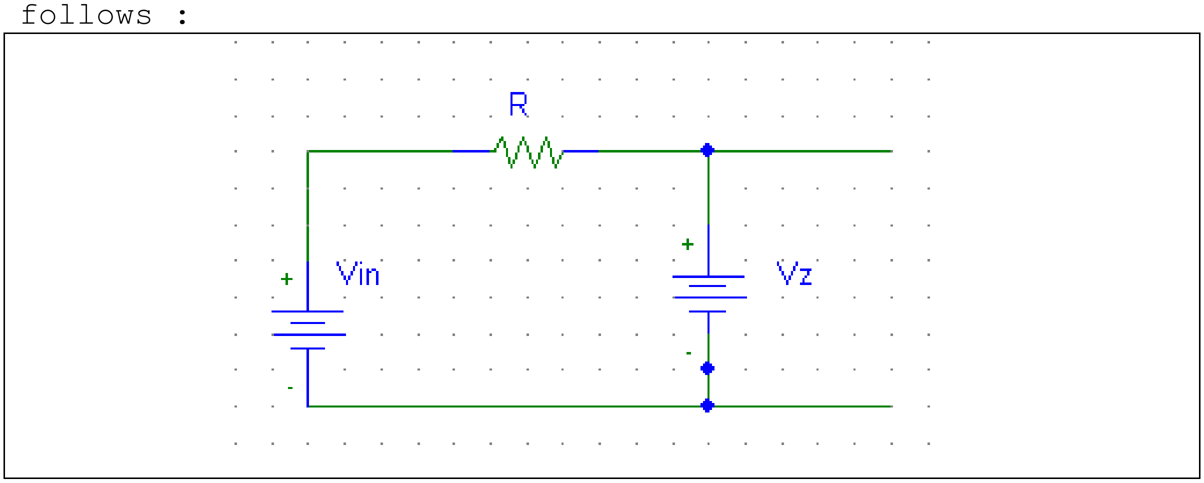


Fig 33 simple voltage regulator circuit

equivalent model for the zener , and assuming that the series resistor (with the power supply) is used to limit the zener current to 80 mA then we can deduce (using Kirchhoff's Law) an expression for the supply current as follows :



3.1.2.2 Voltage Reference Circuit

Given the circuit of Fig 34 and assuming that the zener diode is in it's breakdown region then the voltage at point A will be held constant and can be used as a reference for other voltage input . upon which a particular electronic circuit may be activated or deactivated depending whether a controlling voltage is larger or smaller than the prefixed reference voltage .

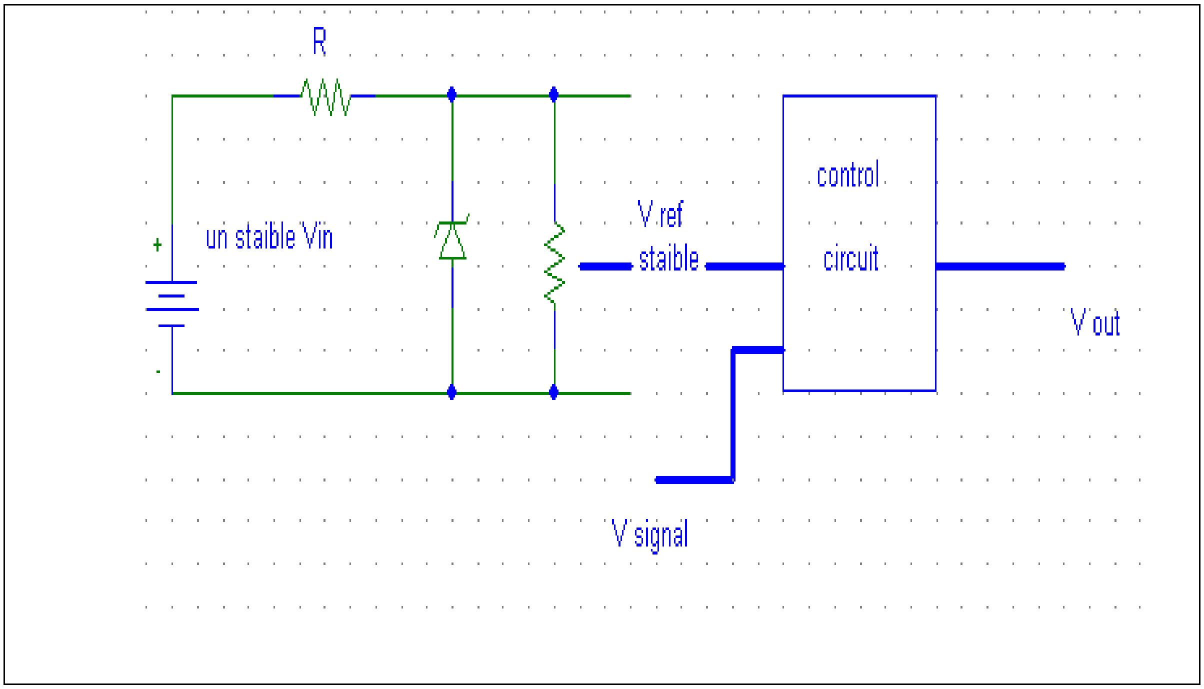
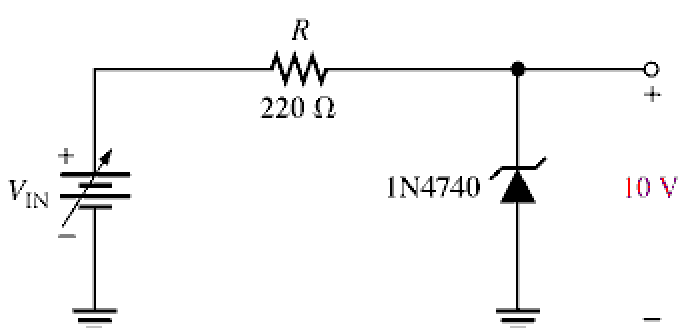


Fig 34 Voltage reference circuit

3.1.2.3 Zener Diode / Analysis examples

Voltage regulator
A zener diode provides nearly constant output voltage across its terminals.
Let's assume a 1N4740 10V zener diode.
It can maintain regulation over currents $I_{ZK} = 0.25$ mA to $I_{ZM} = 100$ mA. We get these values from the data sheet. We would get $P_{D(max)} = 1$ W and $V_Z = 10$ V, from which we can get $I_{ZM} = P_{D(max)}/V_Z = 100$ mA.



Thus, for this circuit, we will get that the voltages

- across resistor R will be

$V_R = I_{ZK} R = (0.25\ mA)(220\ \square) = 55\ mV$

- $V_R = I_{ZM} R = (100\ mA)\ (220\ \square) = 22\ mV$

These voltages result in the following input voltages:

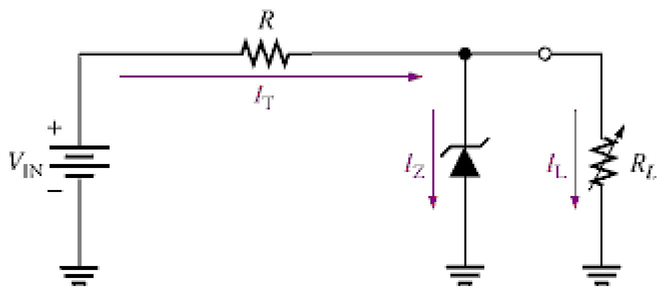
$V_{IN(min)} = V_R + V_Z = 55\ mV + 10\ V = 10.055\ V$

$V_{IN(max)} = V_R + V_Z = 22\ V + 10\ V = 32\ V$

Thus, these zener diode can regulate an input voltage from 10.055 V to 32 V and maintain an approximate 10 V output.

- Output will actually vary slightly due to the zener impedance (neglected in calculations).

Let's look at the case of variable loads (and fixed input).



The zener will maintain a constant voltage across R_L as long as the zener current is between I_{ZK} and I_{ZM}.

To get the boundary values (maximum and minimum loads) we need to find the no load (NL) current.

When there is no load (R = ∞), all current goes through the diode.

We need to verify that the no load current is less than I_{ZM}.

We also need to find what the minimum load is.

The maximum load current, I_L, occurs when current

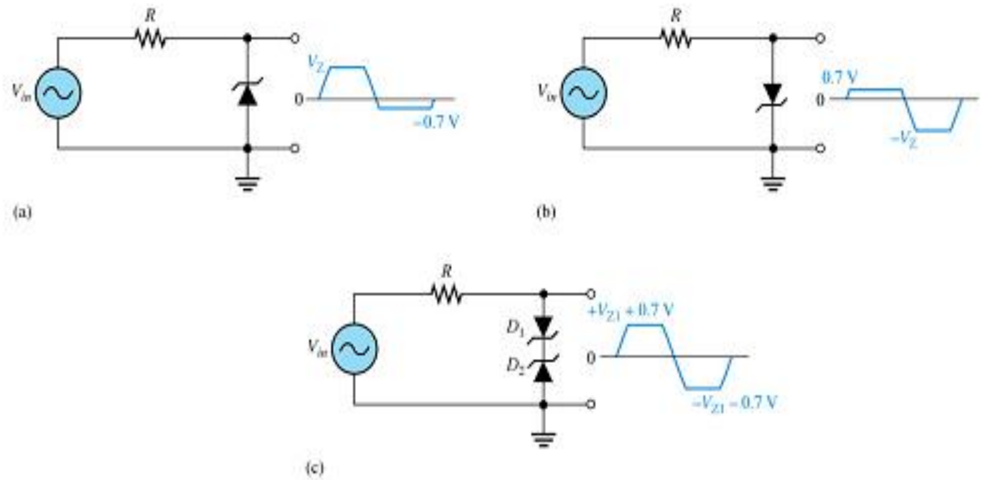
- through diode is minimum, I_{ZK}

$I_{L(max)} = I_{ZM} - I_{ZK}$

We use this value to find the minimum value for R_L.

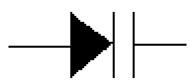
$R_{L(min)} = V_Z/I_{L(max)}$

Example Zener limiting



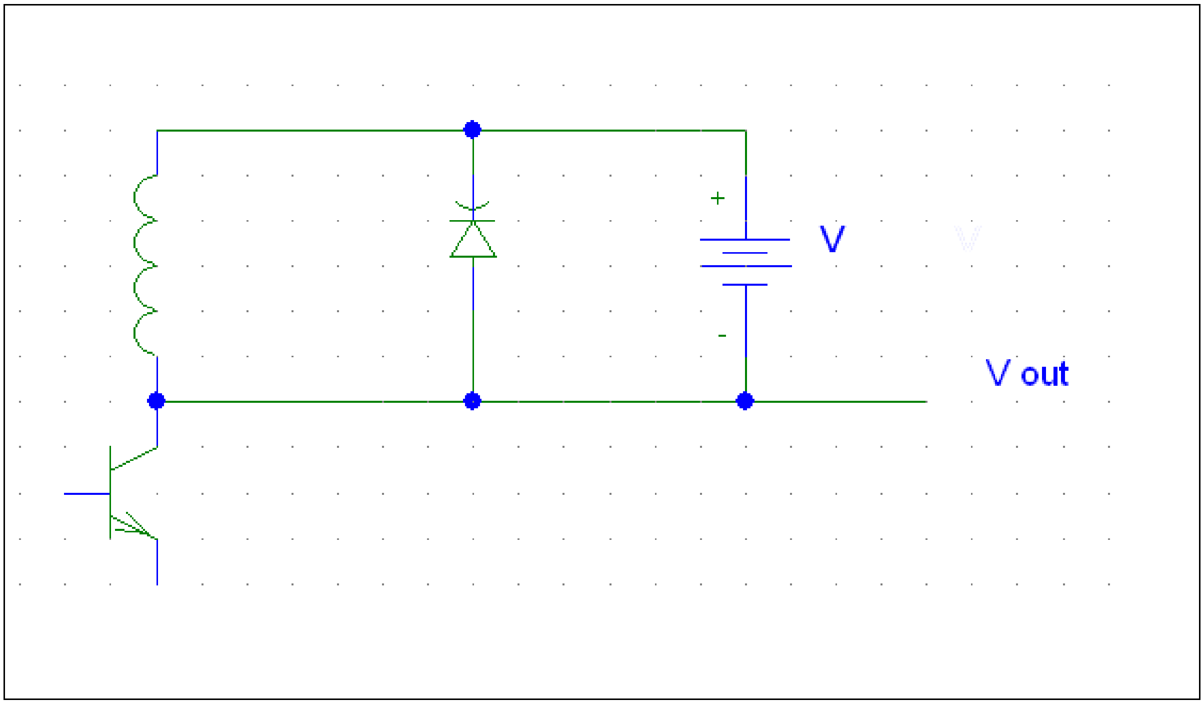
During the positive half-cycle, the diode limits the
output voltage to V_Z.
During the negative half-cycle, the zener limits the output voltage to -0.7 V (forward-biased voltage).
Two back-to-back zeners limit output to $\pm(V_Z + 0.7\text{ V})$ (for positive or negative, respectively.

3.2 **Varactor Diodes**



Such diodes are manufactured in a way as to exploit the capacitance effect(Permittivity of the semiconductor material X area P/N Junction area / Distance between the N and P materials) between the N and P materials across the junction . Usually high doping (to reduce the depletion layer width and thus increase the capacitance effect -- capacitance effect is inversely proportional to the distance between charged areas) levels are used in the semiconductor materials .Exact value for such capacitance (usually in pico Farrad) can be calculated using a number of formulae ,in terms of the electronic parameters of the diode .

Typical applications for such diodes are in Voltage oscillator circuits as shown in Fig (35) .



3.3 The Schottkey diode

This type of diodes use metallic material such as gold in place of the P-type material . Such a structure make use of the free electrons found in the conductor to initiate current flow at very small forward diode voltage ,and because there is no depletion layer diode response is much faster than ordinary diodes which makes them ideal for high speed switching applications (e.g. computer cct , microwave cct etc .) . Fig (36) shows schematic diagram representing this type of diode .

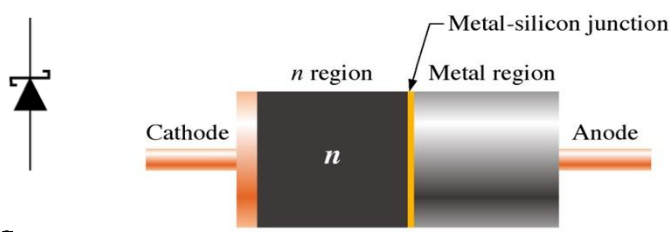


Fig 36

3.4 Tunnel diodes

Increasing the doping of the semiconductor materials to a certain levels will greatly reduce the depletion layer width(less than a millionth of an inch) . A stage could be reached where by a small forward voltage will cause an appreciable forward current , also because of the very thin width of the depletion layer , a small reverse voltage causes a large reverse current . Fig (37) shows a typical tunnel diode I/V response . note the kink in the response at a particular forward current . such a kink (called negative

resistance region) characterizes this type of diode . Because of the very small width of the depletion layer , the diode response is very fast and
thus , as in the case of the schottky diode , it can be used for high speed switching applications .

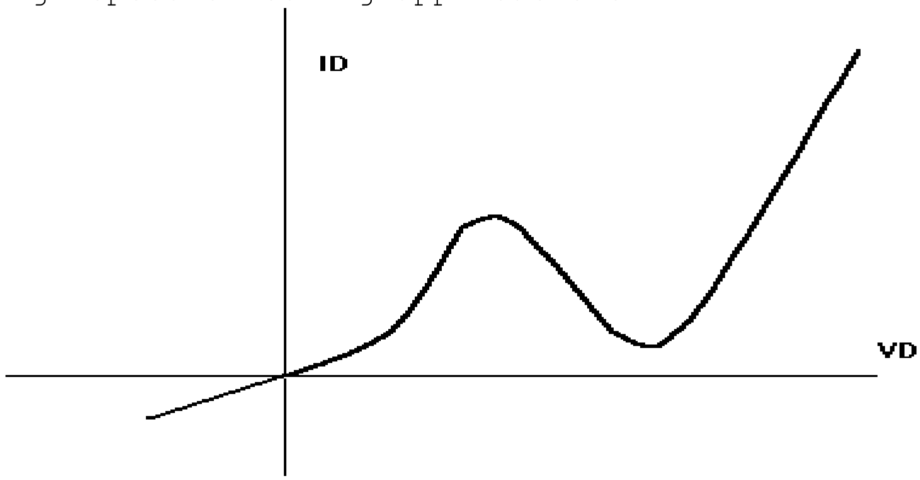


Fig 37 The Tunnel Diode response

3.5 Opto-Electronic diodes

Light may be cosidered as Waves , similar to radio waves , thus it has wavelength and a frequency given by the following formula :

the wavelength = c / f

where c is the speed of light --- 186,000 miles /hour or 3 X 10 8 meters / second

Various light components (e.g. colors , infrared , etc.) have different Wavelengths (Frequencies) ranging from (for this course) 7000 A (1 Angstrom =10 -10 meters)for the infrared component to 3500 A for the Ultraviolt component .

The energy transmitted (as photons) by a source of light is given by the following relationship :
Energy = Constant (called Plank = 6.624 X 10 -34 Joules) X frequency of light emitted by the source .
i.e. transmitted energy is proportional to the frequency of light being transmitted . It is possible to exploite the

light energy in electronic devies as will be explained in the following sections :

3.5.1 Photodiodes

A photodiode is a P/N diode designed to operate with reverse bias voltage applied to it's junction . As explained in earlier section , some small current (leakage) is expected to flow , at room temperature , due to the presence of minority carriers . The level of such current can be increased significantly , if light is allowed to enter the P/n junction area . The energy associated with such a light causes the generation of more electron/holes pairs and thus the large current flow .Applications of such devices are on the increase (e.g. light activated switch , Illumination system controllers , etc.)

3.5.2 Infrared (IR) Emitters .

IR diode is a gallium arsenide (semiconductors materials) which emits light , in the Infrared range (6000 A) , when forward biased . Such a light (not visible) may be used in communications (light) systems e.g. Fiber optics transmitters , Remote controls or security systems , etc. (usually an IR photodiode is used in conjunction with the above diode which acts as an Infrared receiver .

3.5.3 Light emitting diodes LED 's

Light emitting diodes , as the name implies are diodes , gallium / arsenide , which emits light when forward biased. The light produced can be several colors , usually Red , Green , Yellow . Such diode have many applications such as Display systems , Power indicators etc.

3.5.4 Solar cells

A Solar cell is a P/N material structured in such a way as to allow maximum incident light to reached the junction as shown in fig (39) . Such a light will cause the internal resistance of the diode to decrease ..