CHAPTER ONE
ENERGY BANDS IN SOLIDS

1.1. THE NATURE OF THE ATOM:

An atom is the smallest particle of an element that retains the characteristics of the metallic, each atom consist of central nucleus surrounded by orbiting electrons, the consist of positively charges called protons and uncharged particles called neutrons. The electron is the basic unit of the negative charge in atom, where the charge of electron is $1.6x10^{-19}$c and the mass of electron is $9.1x10^{-31}$kg.

Bohr model:

The hydrogen atom, which consist of a positively charge nucleus (proton) equal in magnitude to the negative charge (single electron), but the immobile proton carries all the mass of the atom. As shown in figure (1). Whereas the electron move about it in a closed orbit due to the attraction force ($q^2/4\pi G_o r^2$) between the proton and the electron.

Figure 1: Bohr model

q = the electronic charge in C.

G_o= permittivity of the space ($8.85x10^{-12}$F/m).

r = radius of the orbit.

By Newton's second law of motion, this must equal to the product of the acceleration ($^2/r$) toward the nucleus and the mass of the electron (m).

$$\frac{q^2}{4\pi G_o r^2} = \frac{mv^2}{r}$$

$u = \sqrt{q^2/4\ \ G_o\ mr}$ … … … 1 (the orbital electron velocity m/s)

From equation(1) Bohr postulated the following three fundamental laws:

1) An atom has infinite states of energy, which are separated and the electron in these states is **stationary and non-radiating.**
2) Electromagnetic radiation is emitted from the moving of the electron from an orbit of a total energy E_i to lower orbit of total energy E_f.
   The frequency of the emitted radiation is:
   $$f = \frac{E_i - E_f}{h}$$
   h: Planck constant = 6.626×10^{-34} Joule. Second (J.s).
3) The stationary state is determined by the condition that the angular momentum of the electron is quantized and must be equal to $h/2\pi$,
   $$mur = n\frac{h}{2} \text{ … … … } 2$$
   mvr = orbital angular momentum of the electron.

   n= integer (1, 2, 3,…………,∞)

   From equations (1and 2) we obtain:
   $$r = \frac{h^2 G_o}{q^2\ \pi m} n^2$$
   At $n = 1$ $r = 5.29 \times 10^{-11}$m $= 0.53$Å (Bohr radius)

$a_o = 0.53 Å$ (Bohr radius)

$$r = a_o n^2$$

1.2. ATOMIC ENERGY LEVELS:

The electron energy in orbit is the sum of the kinetic energy E_k and the electrostatic energy mean that:

$$E_k = \frac{1}{2} m u^2$$

$E = E_k +$ electrostatic energy

$$E_k = \frac{1}{2} m * \sqrt{q^2 / 4\pi G_o mr}^2$$

$$E_k = \frac{q^2}{8\pi G_o r}$$

The electrostatic energy is the work, which required moving an electron from the infinity to distance (r) to positive nucleus of atom so:

$$w\ (\text{work}) = -\frac{q^2}{4\pi G_o r}$$

$$E = E_k + w$$

$$E = \frac{q^2}{8\pi G_o r} - \frac{q^2}{4\pi G_o r}$$

$$E = -\frac{q^2}{8\pi G_o r} = -E_k$$

The total energy of electron in orbit is negative, if the total energy is greater than zero, mean that the electron has enough energy to separate from atom.

$$E = -\frac{mq^4}{8h^2 G_o^2} \cdot \frac{1}{n^2}$$

The magnitude $[-mq^4/8h^2G^2_0]$ is constant and equal to $(-13.6eV)$ which represent the (the ground state energy E_R).

$E_R = -13.6eV$

$$E_n = \frac{1}{n^2} E_R \text{ (the electron state energy in orbit) } \ldots \ldots \ldots 3$$

From figure (2) we can conclude that:

1) It is impossible to exit an electron in the gap because there is **forbidden energy.**

2) The total electron energy is quantized.

3) The energy between the two orbits is needed to rise the electron to another orbit.

$$\Delta E = E_R * \frac{1}{n_i^2} - \frac{1}{n_f^2} + \ldots \ldots \ldots 4$$

For each integral value of n in Equation (4) a horizontal lines is drawn, which are arranged vertically in accordance with values calculated from Equation (4). Such representation is called an energy level diagram as in Figure (2) for hydrogen. The number to the left of each line gives the energy of this level in **eV**, and the number to the right is the value of (n). the first five levels and the level for $(n = \infty)$ is indicated in figure (2). it is more common to specify the emitted radiation by its **wavelength** λ **in** Å rather than **frequency** f **in Hz**. So Equation (4) can be rewritten as:

$$\lambda = \frac{12400}{E_i - E_f}$$

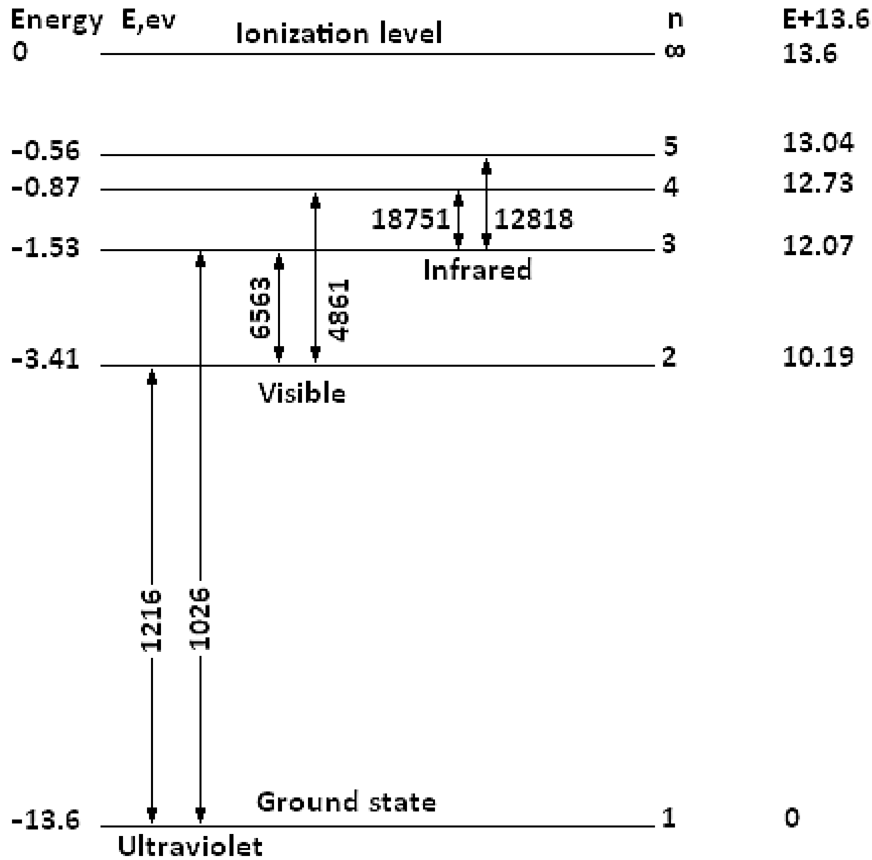


Figure 2: The lowest five energy levels and the ionization level of hydrogen.

Since only difference of energy enter into this equation, the zero state may chose at will. It is normally to choose the lowest energy state as the zero level. As shown in Figure 2, the lowest energy state is called the ground level state, and the other stationary states are called radiating or resonance level states. As the electron is given more and more energy, it moves into stationary states which are farther and farther away from the nucleus. When its energy is large enough to move it completely out of the field of influence of the ion, it become detached from it.This energy is called ionization potential and it is the highest state in the energy level diagram; **13.6eV** for hydrogen.

Example 1:

If the electron energy in 2^{nd} state is -3.41eV, how much energy needed to rise the electron from the 1^{st} state to 2^{nd} state?

Solution:

$$\Delta E = E_R * \frac{1}{n_i^2} - \frac{1}{n_f^2} +$$

$$\Delta E = -13.6 [\frac{1}{2^2} - \frac{1}{1^2}] = 10.19eV$$

Example 2:

The total energy of electron in 2nd state is -3.4eV. Find the w and the k. E in the state and what is the radius of the orbit?

Solution:

$$E = E_k + w$$

$$E = \frac{q^2}{8\pi G_o r} + (-\frac{q^2}{4\pi G_o r})$$

$$E = -\frac{q^2}{8\pi G_o r}$$

$$E = -E_k$$

$$E = -(-3.4eV) = 3.4eV$$

$$w = -2E_k = 2(-3.4eV) = -6.8eV$$

$$r = a_o n^2 = 0.53Å \times 2^2 = 2.12Å$$

Potential energy:

The law of conservation of energy state that the total energy **E**, which equal to the sum of the potential energy U and the E_k, remain constant at any point in space:

$$E = \frac{1}{2} m u^2 + U$$

To describe this law :

Consider that two parallel electrode [A and B as in Figure 3] separated by a distance d, with B at a negative potential V_d respect to A.

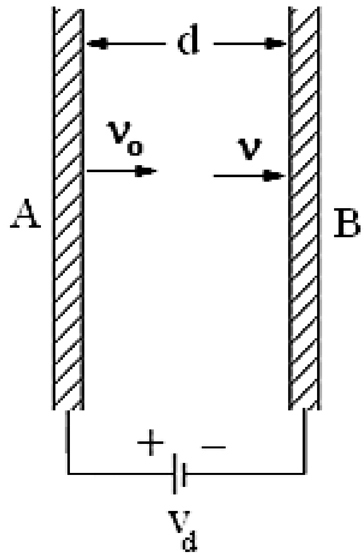


Figure 3: The potential energy

An electron leaves the surface A with velocity v_o in the direction toward B. Since the electron is moving in repelling field this indicates that u must be less than v_o. It is clear also that the differences of potential have meaning.:

$$E = \frac{1}{2} m u_o^2 = \frac{1}{2} m u_d^2 + qV$$

A unit of work or energy called electron volt (eV) as:

$q.V = 1.6 \times 10^{-19} \times 1\text{volt} = 1.6 \times 10^{-19}\text{J} = 1\text{eV}$

1.3. WAVE MECHANICS:

De Broglie Hypothesis (Duality); the dual character of wave and particle (electron, atom, ……..) is not limited to radiation, but the wave is also exhibited as particles. Then the **momentum** of electron is;

$p = mv$

Also the electron behavior as wave;

λ (the wave length) $= \frac{h}{p} = \frac{h}{mu}$ ……… 5

If this electron accelerated in electric field, then the E_k of the electron is equal to the potential energy:

$$\frac{1}{2}mv^2 = qV$$

Then the momentum of the electron is:

$$p = mv = \sqrt{2mqV}$$

$$u = \sqrt{2qV/m} \text{ ……… } 6$$

Substitute the value of (u) from equation(5in 6) to obtain;

$$\lambda = \frac{h}{\sqrt{2mqV}} \text{ ……… } 7 \qquad \text{(De Broglie equation)}$$

For the electron in quantized orbit by the number (n), we can say from equation(2) that:

$$mvr = n\frac{h}{2\pi}$$

$$2\pi r = n.\frac{h}{mv}$$

Since $(\lambda = \frac{h}{mv})$

$$n\lambda = 2\ r \text{ ……… } 8$$

where

n = the integer number of the wave length.

$2\pi r$ = is the length of the orbit.

Example 3:

Find the wave length of the of the electromagnetic radiation, which emitted, when a photon of energy (5eV) for electron transition from orbit to another?

Solution:

$$\Delta E = h \times f = \frac{hc}{\lambda}$$

$$\lambda = \frac{hc}{\Delta E}$$

$$\lambda = \frac{6.626 \times 10^{-34} \times 3 \times 10^{8}}{5 \times 1.6 \times 10^{-19}} = 0.24\mu m$$

Example 4:

Find the wave length of the electromagnetic radiation, which emitted from an atom, when two electrons jump from (5^{th} to 2^{nd}) orbit and the other from (3^{rd} to 1^{st}) orbit? Note that the ground energy equal to (−13.6eV).

Solution:

$$\Delta E = E_R \left(\frac{1}{n_i^2} - \frac{1}{n_f^2}\right)$$

$$\Delta E_1 = -13.6 \left(\frac{1}{5^2} - \frac{1}{2^2}\right) = 2.856eV$$

$$\Delta E_2 = -13.6 \left(\frac{1}{3^2} - \frac{1}{1^2}\right) = 12.09eV$$

$$\Delta E = hf = h\frac{c}{\lambda}$$

$$\lambda = \frac{hc}{\Delta E} = \frac{hc}{q} \times \frac{1}{\Delta E}$$

$$\frac{hc}{q} = \frac{3 \times 10^{8} \times 6.626 \times 10^{-34}}{1.6 \times 10^{-19}} = 1.24\mu \frac{J.m}{C}$$

$$\lambda_1 = \frac{1.24}{2.85} = 435 \text{ nm}$$

$$\lambda_2 = \frac{1.24}{12.09} = 102 \text{ nm}$$

Example 5:

Determine the frequency of the wave length which emitted from an atom has an electron transited from(3rd orbit and then from 2nd orbit to 1st orbit)? Note that the ground energy equal to (−13.6ev).

Solution:

$$\Delta E_1 = -13.6\left(\frac{1}{3^2} - \frac{1}{2^2}\right) = 1.9eV$$

$$\Delta E_2 = -13.6\left(\frac{1}{2^2} - \frac{1}{1^2}\right) = 10.2eV$$

$$\Delta E = hf$$

$$f = \frac{\Delta E}{h} = \frac{q \times \Delta E}{h}$$

$$f_1 = \frac{1.9 \times 1.6 \times 10^{-19}}{6.626 \times 10^{-34}} = 5.45 \times 10^{14} \text{ Hz}$$

$$f_2 = \frac{10.2 \times 1.6 \times 10^{-19}}{6.626 \times 10^{-34}} = 2.92 \times 10^{15} \text{ Hz}$$

1.4. The energy band theory of crystals

In energy band of atom, all the electrons of a given atom having the same value of n belong to the same prescribed bands (electronic shell). Each shell around the nucleus corresponds to a certain energy band and is separated from adjacent shells by energy gaps, in which no electron can exist.

A crystal is a solid consisting of a regular and repetitive arrangement of atoms or molecules in space. If the positions of the atoms in the crystal are represented by points, called lattice points, we get a crystal lattice. The distance between the atoms in a crystal is fixed and is termed the lattice constant of the crystal.

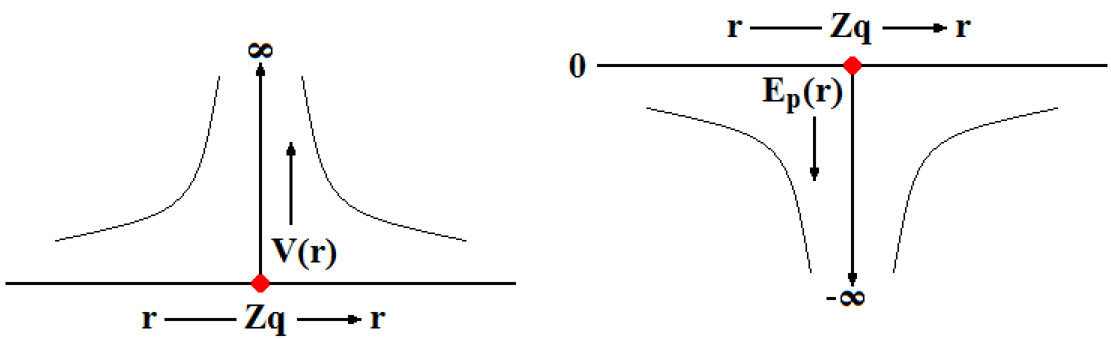
To discuss the behavior of electrons in a crystal, we consider an isolated atom of the crystal. If **Z** is the atomic number, the atomic nucleus has a positive charge **Zq**. At a distance r from the nucleus, the electrostatic potential due to the nuclear charge is (in SI units).

$$V(r) = \frac{Zq}{4\ G_o r} \quad \ldots\ldots\ldots 9$$

Since an electron carries a negative charge, the potential energy of an electron at a distance r from the nucleus is:

$$E_p(r) = -qV = -\frac{Zq^2}{4\ G_o r} \quad \ldots\ldots\ldots 10$$

V (r) is positive while $E_p(r)$ is negative. Both V (r) and $E_p(r)$ are zero at an infinite distance from the nucleus. Figures 4(a) and (b) show the variation of V (r) and $E_p(r)$, respectively with r.



(a) (b)

Figure 4: Variation of (a) Potential in the field of a nucleus with distance, (b) Potential energy of an electron with its distance from the nucleus.

Now, consider two identical atoms placed close together. The net potential energy of an electron is obtained as the sum of the potential energies due to the two individual nuclei. In the region between the two nuclei, the net potential energy is clearly smaller than the potential energy for an isolated nucleus (see Figure 5).

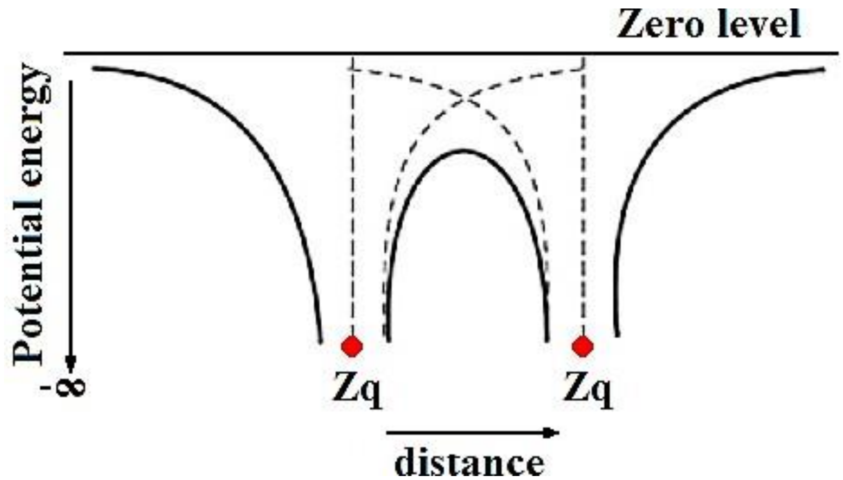


Figure 5: Potential energy variation of an electron with distance between two identical nuclei.

The potential energy along a line through a row of equispaced atomic nuclei, as in a crystal, is shown in Figure 6a. The potential energy between the nuclei is found to consist of a series of humps. The separation between the split-off energy levels is very small. This large number of discrete and closely spaced energy levels forms an energy band. Energy bands are represented schematically by shaded regions in Figure 6b.

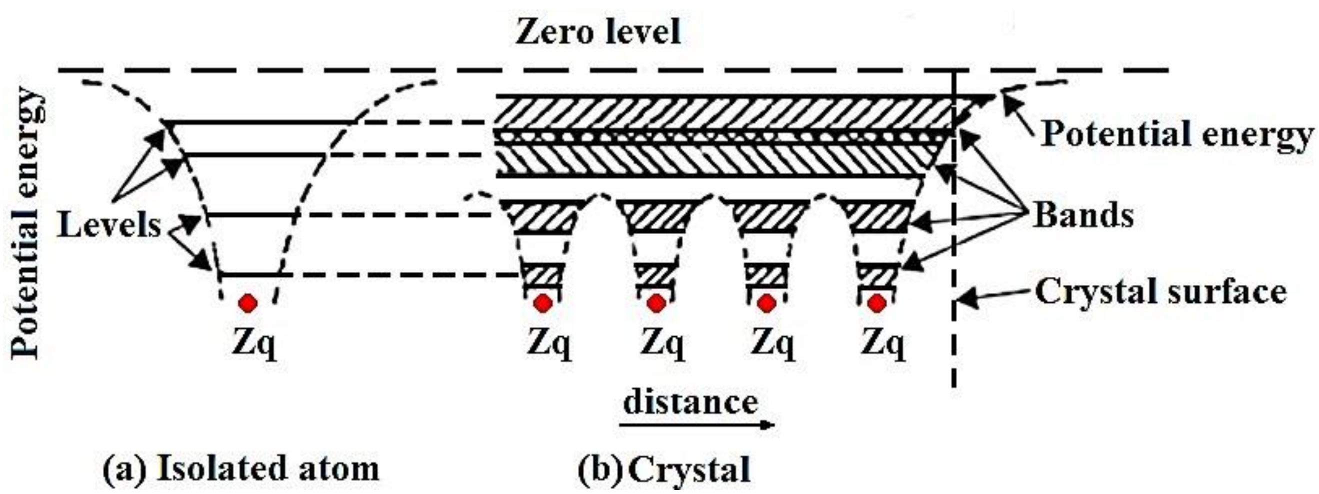


Figure 6: Splitting of energy levels of isolated atoms into energy bands as these atoms are brought close together to produce a crystal.

The width of an energy band is determined by the parent energy level of the isolated atom and the atomic spacing in the crystal. The lower energy levels are not greatly affected by the interaction among the neighboring atoms, and hence form narrow bands.

The higher energy levels are greatly affected by the interatomic interactions and produce wide bands.

The lower energy bands are normally completely filled by the electrons since the electrons always tend to occupy the lowest available energy states. The higher energy bands may be completely empty or may be partly filled by the electrons.

The lower energy band calls the valence band and the first, un filled or partially filled, band above the valence is called conduction band. The energy gap between the valence and conduction can be calculated as:

$$E_g = E_c - E_v$$

On the basis of the band structure, crystals can be classified into metals, insulators, and semiconductors.

Insulator:

The insulator Have a large forbidden gap$> 3 - 10$eV, separate the filled valence band from the vacant conduction band (Example: the forbidden gap for the carbon = 6eV). The applied energy to an electron is too small to carry it from the filled band to the vacant band. So the conduction is impossible and the carbon is an Insulator.

Conductor:

Under the effect of an applied electric field, the electrons acquire additional energy and move into higher state. Since these mobile electrons result a current, this solid is a conductor, and the filled region is the conduction band. Overlapping is happen between the valence and conduction bands.

Semiconductor:

The forbidden gap is small < 2eV (germanium and silicon) at 0^oK. Energy cannot be acquired from an applied field, so the valence band remains fill, and the conduction band empty, and it is insulator at low temperature. At the temperature increase, some of these valence electrons obtain thermal energy greater than E_g, and the electrons move into conduction band.

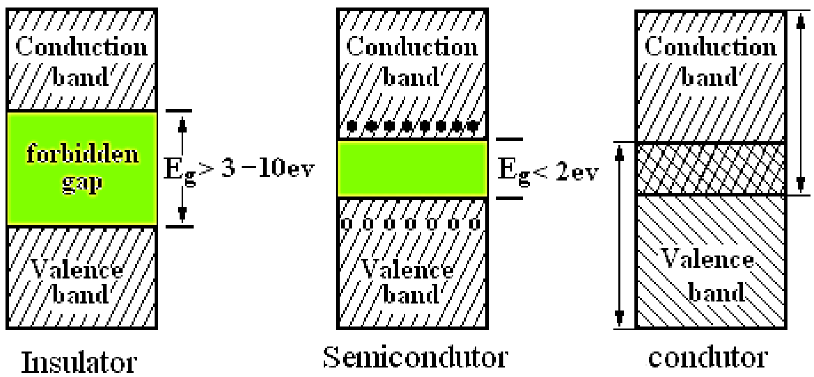


Figure 7: The energy gap in solids

At the temperature increase, some of these valence electrons obtain thermal energy greater than E_g, and the electrons move into conduction band. These are free electrons can move under the effect of a small applied field, and result a current. The Insulator has now become slightly conducting; it is a Semiconductor, which has a free electrons in a conduction band and a holes in a valence band.

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PHYSICAL

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Chapter two

Transport Phenomena in Semiconductor

Electronic Physics for First Class

Systems and Control Department

Chapter two: Transport phenomena in S.C.

2-1 Intrinsic Semiconductor and Extrinsic Semiconductor

The semiconductor is divided into two types:

2-1-1 Intrinsic (pure) semiconductor

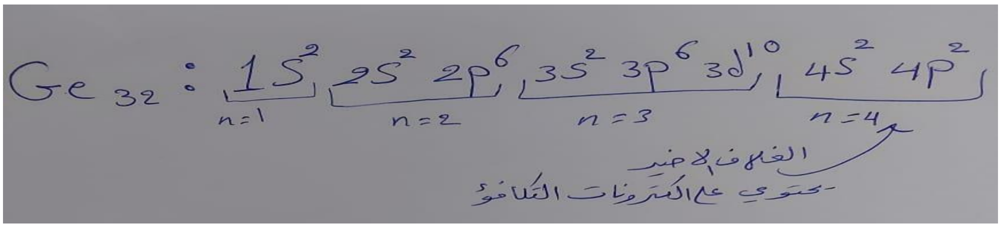
The pure form of the semiconductor is known as the Intrinsic semiconductor. The conductivity of this type becomes zero at room temperature.

In a **pure (intrinsic) semiconductor** the number of holes is equal to the number of free electrons. Thermal agitation continues to produce new hole-electron pairs, whereas other hole-electron pairs disappear as a result of recombination. The hole concentration *p* must equal the electron concentration *n*, so that

$$\mathbf{n = p = n_i}$$

where: n_i is called the intrinsic concentration.

example:



Germanium (Ge) is the most important semiconductor used in electronic devices. The crystal structure of Ge is shown in Fig. 2.1

عند درجة حرارة 0 سليزي:

جميع االلكترونات في حزمة التكافؤ مكونة اواصر تساهمية ولاتوجد الكترونات حرة تعتبر بذلك المادة عازلة.

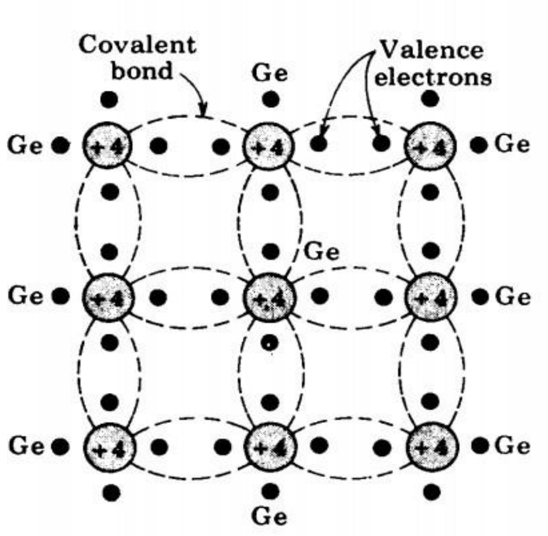


Fig. 1.1 Crystal structure of Germanium.

At Zero temperature the ideal structure of Fig.1.1 is approached, and the crystal behaves as an **insulator**, since no free carriers of electricity are available.

At room temperature (22C), some of the covalent bonds will be broken because of the thermal energy supplied to the crystal, and **conduction is made possible**. This situation is illustrated in Fig.1.2.

عند درجة حرارة الغرفه تقريبا 22C:

تنكسر بعض االواصر التساهمية وتتحرر االلكترونات الى حزمة التوصيل مولدة فجوات مكانها في حزمة التكافؤ.

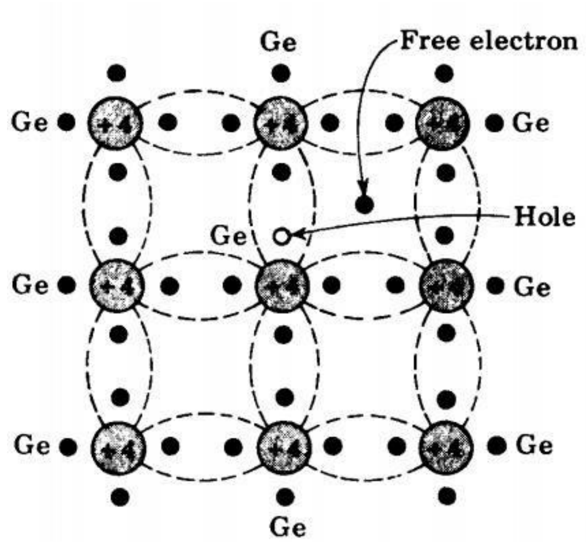
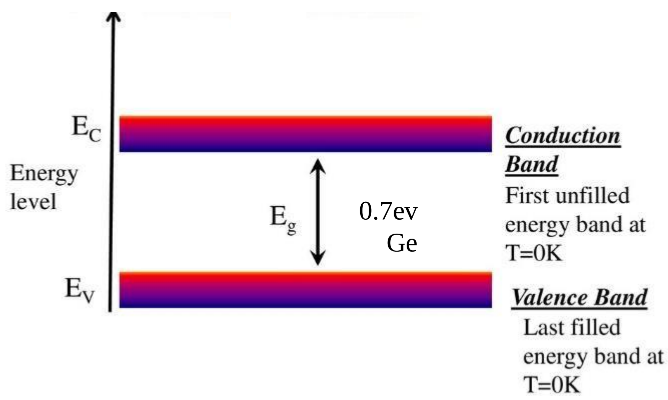


Fig. 1.2 Germanium crystal with a broken covalent bond.

The absence of the electron in the covalent bond is represented by the small circle in Fig.1.2, and such an incomplete covalent bond is called a

hole. The importance of the hole is that it may serve as a carrier of electricity comparable in effectiveness with the free electron.

The energy required to break such a covalent bond is about **0.7 eV for Germanium at room temperature** as in figure below.



2-1-2Extrinsic semiconductor

The semiconductor in which intentionally impurities is added for making it conductive is known as the Extrinsic semiconductor. The conductivity of this type is very less conductive at room temperature.

An intrinsic semiconductor is capable to conduct a little current even at room temperature, but it is not useful for the preparation of various electronic devices. Thus, to make it conductive a small amount of suitable impurity is added to the material.

2-2Doping

The process by which an impurity is added to a semiconductor is known as **Doping**. The amount and type of impurity which is to be added to the material have to be closely controlled during the preparation of extrinsic semiconductor.

Generally, one impurity atom is added to 10^8 atoms of a semiconductor. The purpose of adding impurity in the semiconductor crystal is to increase the conductivity by raising the number of free electrons or holes.

Depending upon the type of impurity added, the extrinsic semiconductor may be classified as:

1- n-type semiconductor.
2- p-type semiconductor.

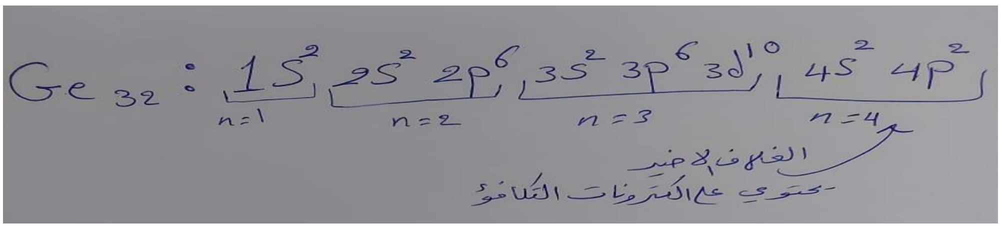
2-2-1 n-type semiconductor

When a small amount of **Pentavalent impurity** is added to a pure semiconductor providing a large number of free electrons in it, the extrinsic semiconductor thus formed is known as n-type semiconductor. The conduction in the n-type semiconductor is because of the free electrons denoted by the pentavalent impurity atoms.

The addition of pentavalent impurities (such as arsenic (As), antimony (Sb) and phosphorus (P)) provides a large number of free electrons in the semiconductor crystal. Such impurities which produce n-type semiconductors are known as **Donor Impurities**.

They are called a donor impurity because each atom of them donates one free electron crystal.

example: crystal lattice with a germanium atom doped by antimony (sb) atom.



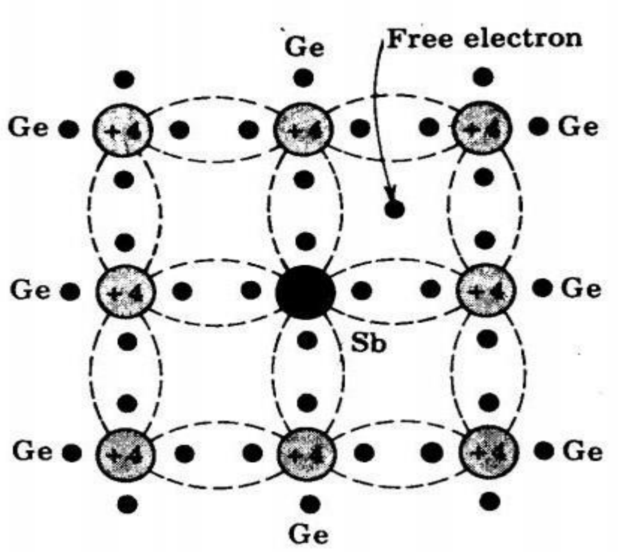


Fig. 1.3 Crystal lattice with a Germanium atom displaced by a pentavalent impurity atom (sb).

When donor impurites (sb) are added to the intrinsic semiconductor, allowable energy levels are introduced as very samll distance below the conduction band, as is shown in Fig. 1.4. In the case of **Germanium, the distance of the new discrete allowable energy level is only 0.01 eV (0.05 eV in Silicon) below the conduction band,** and therefore at room temperature almost all the “fifth” electrons of the donor material are raised into the conduction band.

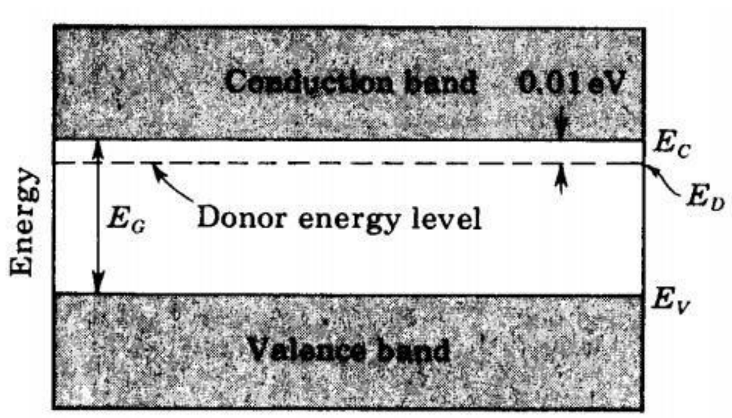
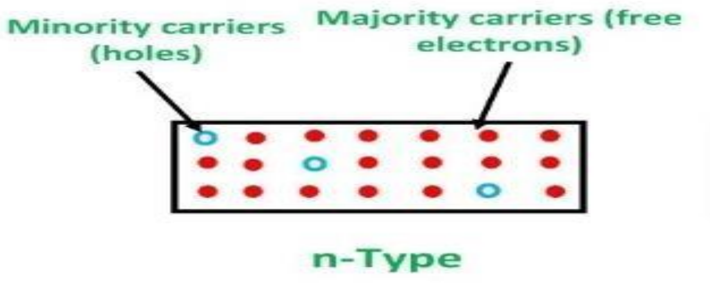


Fig. 2.4 Energy band diagram of n-type semiconductor.

2.2.1.1Majority and Minority Carriers in an n-type Semiconductor

In an n-type semiconductor, the electrons are the **majority** carriers whereas, the holes are the **minority** carriers as shown in figure below:



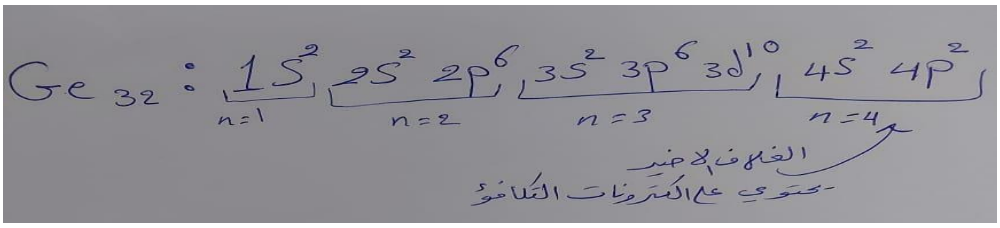
An n-type semiconductor contains a large number of free electrons and a few numbers of holes. This means the electron provided by pentavalent impurity added and share of electron-hole pairs. Therefore, in n-type semiconductor, most of the current conduction is due to the free electrons available in the semiconductor. So, in this type:

n >> p

2.2.2p-type semiconductor

The extrinsic p-type semiconductor is formed when a trivalent impurity is added to a pure semiconductor in a small amount, and as result, a large number of holes are created in it. A large number of holes are provided in the semiconductor material by the addition of trivalent impurities like boron (B) , gallium (GA) and indium (I). such types of impurities which produce p-type semiconductor are known as an **Acceptor Impurities** because each atom of them create one hole which can accept one electron.

Example: crystal lattice with a germanium atom doped by indium (I) atom .



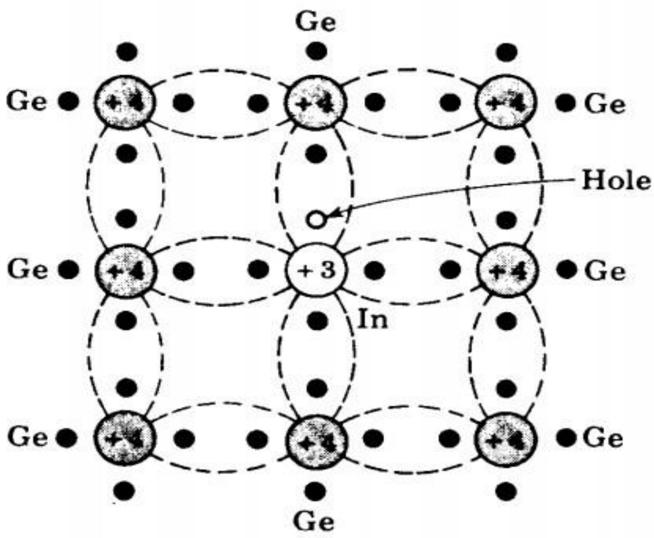


Fig. 1.5 Crystal lattice with a Germanium atom displaced by an atom of trivalent impurity.

In Fig. 1.5, indium (In) atom is added to germanium crystal therefore only three of the covalent bonds can be filled, and the vacancy that exists in the fourth bond constitutes a hole.

When acceptor impurities are added to the intrinsic semiconductor, they produce an allowable discrete energy level which is just above the valence band, as shown in Fig. 1.6. Since a very small amount of energy is required for an electron to leave the valence band and occupy the acceptor energy level, it follows that the holes generated in the valence band by these electrons constitute the largest number of carriers in the semiconductor material.

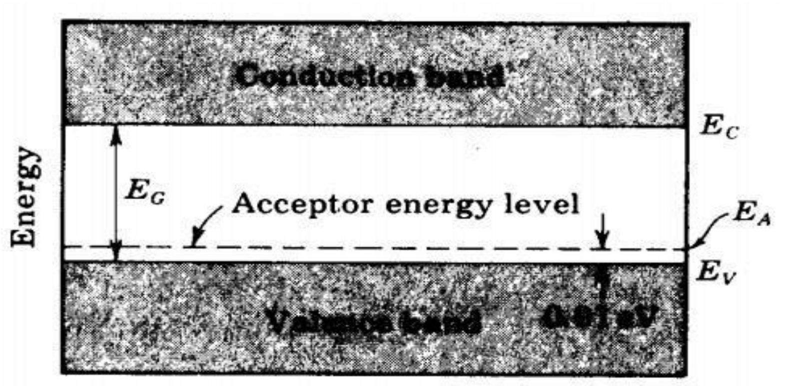
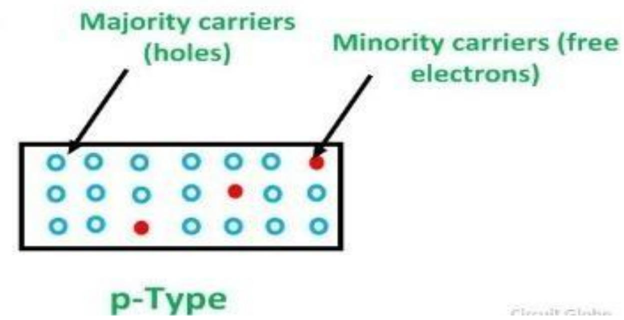


Fig. 1.6 Energy band diagram of p-type semiconductor.

2.2.2.1Majority and Minority Carriers in an p-type Semiconductor

In the p-type semiconductor material, the holes are the **majority** carriers whereas, the electrons are the **minority** carriers as shown in figure below:



In the p-type semiconductor, the holes are in the majority as compared to electrons, and the conduction takes place because of the very few electrons which are present in the minority. So, in this type:

p >> n

2.3Mass Action Low

In electronics and semiconductor physics, the law of mass action is a relation about the concentrations of free electrons and electron holes under thermal equilibrium. It states that, under thermal equilibrium, the product of the free electron concentration n and the free hole concentration p is equal to a constant square of intrinsic carrier concentration n_i^2. This relationship is called the *mass action low* and is given by:

$$n \times p = n_i^2 \qquad \ldots\ldots\ldots (1.1)$$

In **n-type semiconductor,** the density of electrons is approximatly equal to the density of donor atoms.

$n = N_D$ majority carriers (electrons) ……. (1.2)

Where N : concentration of Donor atoms.

So, eqn. (1.1) for this type can be written as:

$$N_D \times p = n_i^2 \qquad \ldots\ldots\ldots (1.3)$$

Similarly, for **p-type semiconductor**:

$p = N_A$ $\quad mijority\ carriers\ (holes)$

N : concentration of Acceptor atoms.

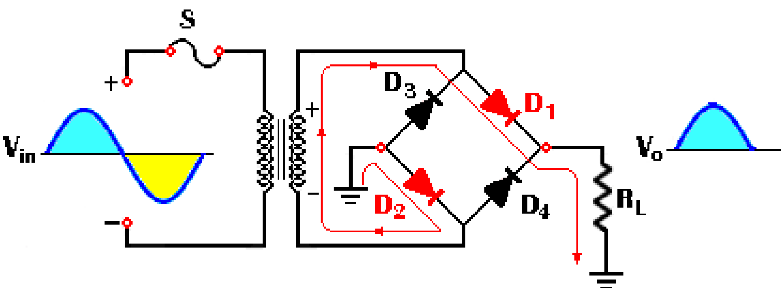
The mass action low for this type can be written as:

$$n \times N_A = n_i^2 \qquad \ldots\ldots. (1.4)$$

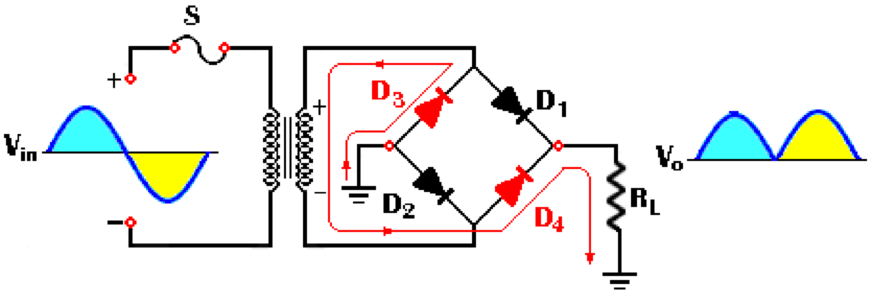
Full wave Rectifier :

The Bridge Full wave Rectifier:

The bridge rectifier uses four diodes connected as shown in figure 11. When the input cycle is positive as shown in figure11a, diodes **D_1** and **D_2** are forward biased and conduct current in the direction shown.



(a) During the positive half cycle of the input.



(b) During the negative half cycle of the input.

Figure 11: Operation of a bridge rectifier.

A voltage is developed across **R_L** that looks like the positive half of the input cycle. During this time, **D_3** and **D_4** are reverse biased. When the input cycle is negative as in figure11b, **D_3** and **D_4** are forward biased and conduct current in the same direction through **R_L** as during the positive half cycle. During the negative half cycle, **D_1** and **D_2** are reverse biased. A full wave rectified output voltage appears across **R_L** as a result of this action.

Bridge output voltage:

During the positive half cycle of the total secondary voltage, diodes D_1 and D_2 are forward biased. Neglecting the diode drops, the secondary voltage appears across the load resistor. The same is true when D_3 and D_4 are forward biased during the negative half cycle.

$$V_{p(out)} = V_{p(sec)}$$

Figure12. Two diodes are always in series with the load resistor during both the positive and negative half cycles. If these diode drops are taken into account, the output voltage is:

$$V_{p(out)} = V_{p(sec)} - 1.4V$$

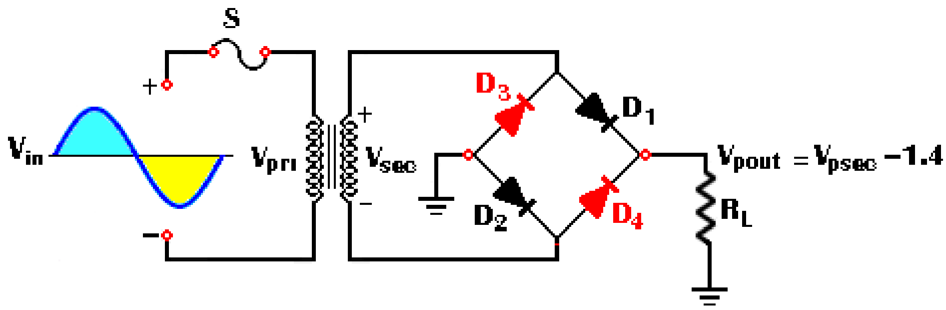


Figure 12: Bridge operation during a positive half cycle of the primary and secondary voltages.

Example 6:

Determine the peak output voltage for the bridge rectifier in figure 12. Assuming the practical model? The transformer is specified to have a 12V rms secondary voltage for the standard 110V across the primary.

Solution:

The peak output voltage (taking into account the two diode drops) is

$$V_{P(sec)} = \sqrt{2} \times 12 = 17V$$

$$V_{P(out)} = V_{P(sec)} - 1.4 = 17 - 1.4 = 15.6V$$

4.3. POWER SUPPLY FILTERS AND REGULATORS:

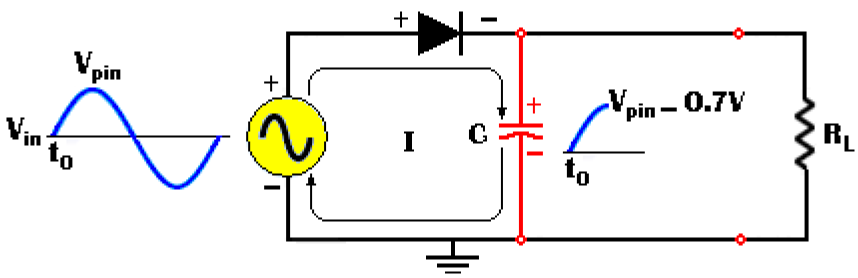
In most power supply applications, the standard 60 Hz ac power line voltage must be converted to an approximately constant dc voltage. The pulsating dc output of a rectifier must be filtered to reduce the large voltage variations.

1. Capacitor Input Filter:

The filter is simply a capacitor connected from the rectifier output to ground. $R_L$represent the equivalent resistance of a load.

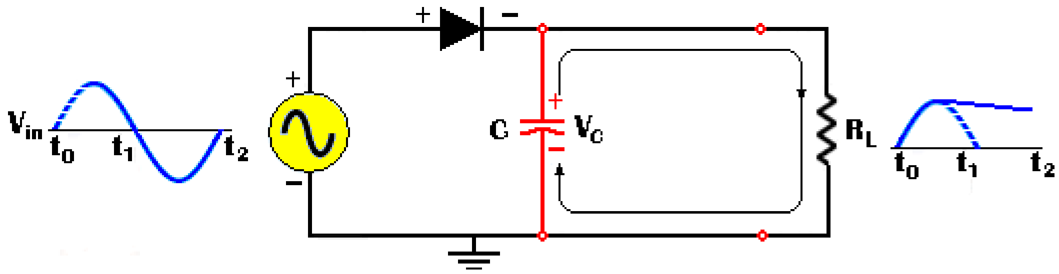
During the positive first quarter cycle of the input, the diode is forward biased, allowing the capacitor to charge to within 0.7 V of the input peak, figure13 a.

When the input begins to decrease below its peak. figure13b, the capacitor retains its charge and the diode becomes reverse biased because the cathode is more positive than the anode.

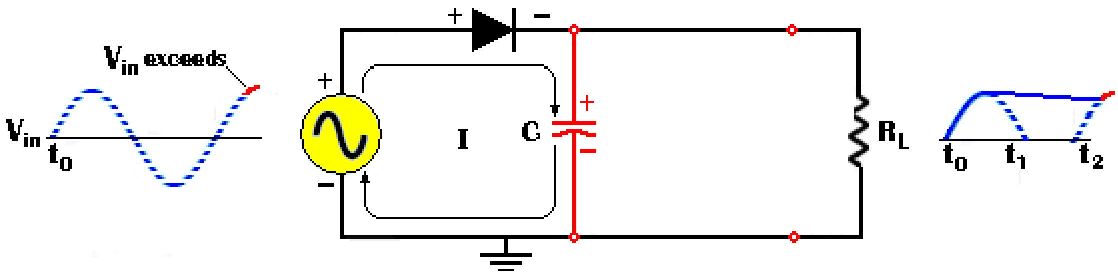


(a) Initial charging of the capacitor (diode is forward biased)

During the remaining part of the cycle, the capacitor can discharge only through the load resistance at a rate determined by R_LC time constant.



(b) The capacitor discharges through R_L after peak of positive alternation when the diode is reverse biased



(c) The capacitor charges back to peak of input when the diode becomes forward-biased.

Figure13: Operation of a half wave rectifier with a capacitor input filter

During the first quarter of the next cycle, figure13c, the diode will again become forward biased when the input voltage exceeds the capacitor voltage by approximately 0.7V.

Ripple Voltage:

The variation in the capacitor voltage due to the charging and discharging is called the ripple voltage. Generally, ripple is undesirable; thus, the smaller the ripple, the better the filtering action, as shown in figure14.

When filtered, the full wave rectified voltage has a smaller ripple than does a half wave voltage for the same load resistance and capacitor values. The capacitor discharges less during the shorter interval between full-wave pulses, as shown in figure14.

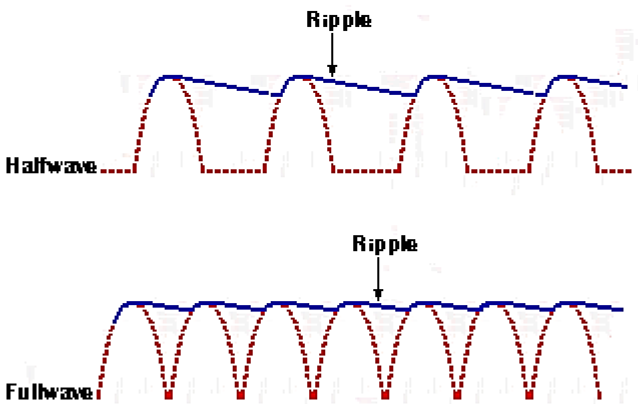


Figure14:Comparison of ripple voltages for half wave and full wave rectified voltages with the same filter capacitor and load

Ripple factor:

The ripple factor is an indication of the effectiveness of the filter and is defined as:

$$\mathbf{r} = \frac{\mathbf{V_r}}{\mathbf{V_{d.c}}}$$

V_r: The peak to peak voltage.

$V_{d.c}$: The d.c (average) value of the filter's output voltage .

As shown in figure15. The ripple factor can be lowered by increasing the value of the filter capacitor or increasing the load resistance. For a full wave rectifier with a capacitor input filter, approximations for the peak to peak ripple voltage, $V_r$and the dc value of the filter output voltage. $V_{d.c}$, are given in the following expressions. The variable $V_{p(rect)}$ is the unfiltered peak rectified voltage.

$$V_r \cong \frac{1}{f R_L C} V_{p(rect)}$$

$$V_{dc} \cong \left(1 - \frac{1}{2 f R_L C}\right) V_{p(rect)}$$

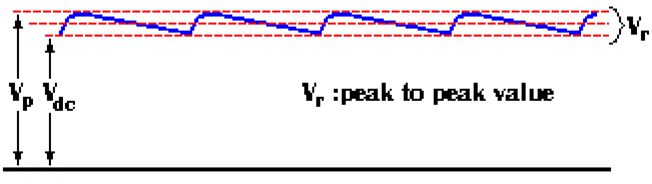
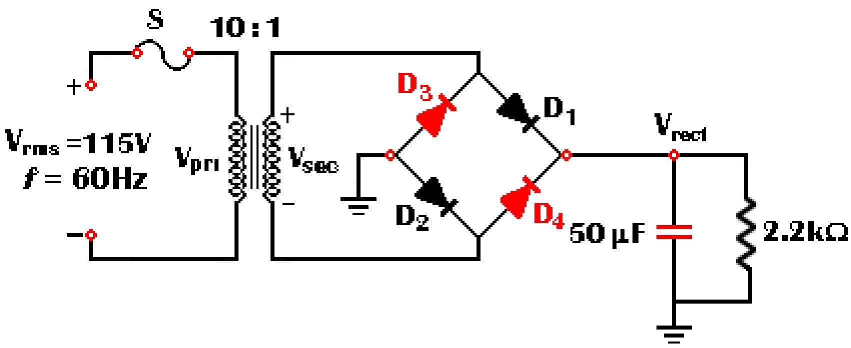


Figure 15: V_r and V_{dc} determine the ripple factor

The last formulas are for ripple filtered signal

Example 7:

Determine the ripple factor for the filtered rectifier with a load as indicated in figure?



Solution:

$$V_{rms} = \frac{V_p}{\sqrt{2}}$$

$$V_{p(pri)} = \sqrt{2} \times V_{rms}$$

$$V_{p(pri)} = \sqrt{2} \times 115 = 163V$$

$$n = \frac{N_2}{N_1} = \frac{1}{10} = 0.1$$

$$V_{p(sec)} = nV_{p(pri)}$$

$$V_{p(sec)} = 0.1 \times 163 = 16.3V$$

The unfiltered peak full wave rectifier voltage is:

$$V_{p(rect)} = V_{p(sec)} - 2V_D = 16.3 - 2 \times 0.7 = 14.9V$$

The frequency of a full wave rectifier voltage is 120Hz. So the ripple voltage is:

$$V_r \cong \left(\frac{1}{f R_L C}\right) V_{p(rect)} = \left(\frac{1}{120 \times 2.2 \times 10^3 \times 50 \times 10^{-6}}\right) \times 14.9 = 1.13V$$

$$V_{dc} \cong \left(1 - \frac{1}{2 f R_L C}\right) V_{p(rect)} = \left(1 - \frac{1}{2 \times 120 \times 2.2 \times 10^3 \times 50 \times 10^{-6}}\right) \times 14.9 = 14.3V$$

$$r = \frac{V_r}{V_{d.c}} = \frac{1.13}{14.3} = 0.079$$

$\therefore r = 7.9\%$

Example 8:

What is the value of C_{min} that required a ripple factor no greater than 0.05, for a full wave bridge rectifier has R_L =10kΩ? Note that: f =50Hz.

Solution:

C_{min} is required when $\mathbf{V_{p(rect)}} = \mathbf{V_{dc}}$

$$\because V_r = \frac{1}{fR_LC} V_{p(rect)}$$

so we can say $V_r = \frac{1}{fR_LC} V_{dc}$

$$r = \frac{V_r}{V_{d.c}} = \frac{(1/fR_LC)V_{dc}}{V_{dc}} = \frac{1}{fR_LC}$$

$$C_{min} = \frac{1}{rfR_L} = \frac{1}{0.05 \times 50 \times 10^4} = 40\mu F$$

2. Inductor Input Filter:

When a choke is add to the filter input, as in figure16, a reduction in the ripple voltage V_r is achieved. The choke has a high reactance at the ripple frequency. And the capacitive reactance is low compared to both R_L and X_L(10 time at least).The magnitude of the out ripple voltage of the filter is determined with voltage divider equation:

$$V_{r(out)} = \frac{X_C}{X_L - X_C} V_{r(in)}$$

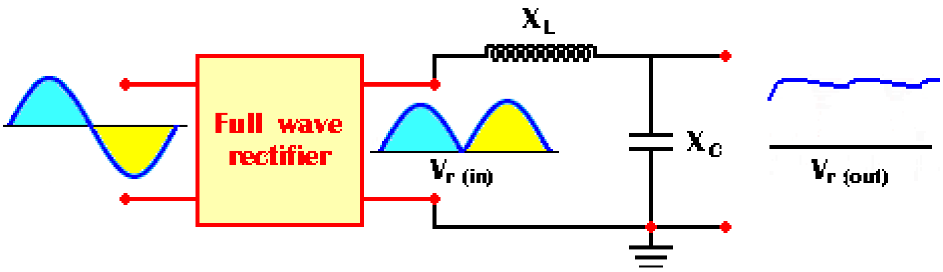


Figure16: the LC filter as it look to the ac component

Since the choke presents a winding resistance R_w in series with load resistance R_L. This resistance produce undesirable reduction of dc value, therefore R_w must be small compared of R_L.

$$V_{dc(out)} = \frac{R_L}{R_w + R_L} V_{dc(in)}$$

Example 9:

A 120Hz full wave rectified voltage with a peak of 163V is applied to LC filter. If the load resistance $R_L = 10k\Omega$, $R_w = 100\Omega$, $L = 1H$ and $C = 50\mu F$. Determine:

a) The output filter in terms of it's dc value?
b) Ripple factor (r)?

Solution:

a) $V_{dc} = V_{avg} = \frac{2V_{p(rect)}}{\pi} = \frac{2 \times 163}{\pi} = 103.7V$

$$V_{dc(out)} = \frac{R_L}{R_w + R_L} V_{dc(in)} = \frac{1000}{100 + 1000} \times 103.7 = 94.3V$$

b) $V_{ac} = V_{r(in)} = 0.308 \times V_p = 0.308 \times 163 = 50.2V$

$$X_L = 2\pi f L = 2 \times 120 \times \pi \times 1 = 754.5\Omega$$

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 120 \times 50 \times 10^{-6}} = 26.5\Omega$$

$$V_{r(out)} = \frac{X_C}{|X_L - X_C|} V_{r(in)} = \frac{26.5}{754.3 - 26.5} \times 50.2 = 1.82V$$

The ripple factor:

$$r = \frac{V_r}{V_{d.c}} = \frac{1.82}{94.3} = 0.0193$$

$r = 1.93\%$

5. DIODE CLIPPING AND CLAMPING CIRCUITS:

Diode circuits, called limiters or clippers, are sometimes used to clip off portions of signal voltages above or below certain levels. Another type of diode circuit, called a clamper, is used to add or restore a dc level to an electrical signal.

1. Diode Clippers:

Positive clippers:

Figure 17 shows a diode clipper that clips the positive part of the input voltage. As the input voltage goes positive, the diode becomes forward biased and conducts the current. So point A is limited to (+0.7V), when the input go back below 0.7v, the diode is reverse biased and appears as an open the output voltage is look like the negative part of the input voltage, but with magnitude determined by the voltage divider formed by R_1 and the load resistance R_L, as follow:

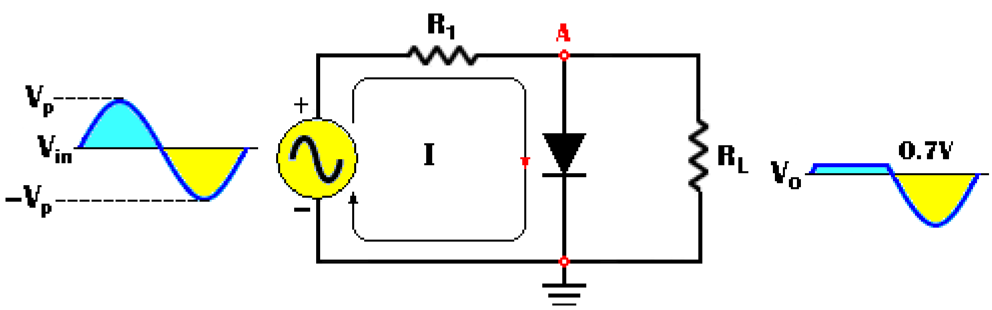


Figure 17: Circuit for the positive clipper

$$V_{out} = \left(\frac{R_L}{R_L + R_1}\right) V_{in} \quad \text{If } R_1 \ll R_L \quad \rightarrow \quad V_{out} = V_{in}$$

Negative clippers:

If the diode turns around as in figure 18, the negative part of the input voltage is clip off. When the diode is forward biased during the negative part of the input voltage, point A is held at (−0.7V) by the diode drop. When the input voltage goes above (−0.7V), the diode is no longer forward biased; and a voltage appears across R_L proportional to the input voltage.

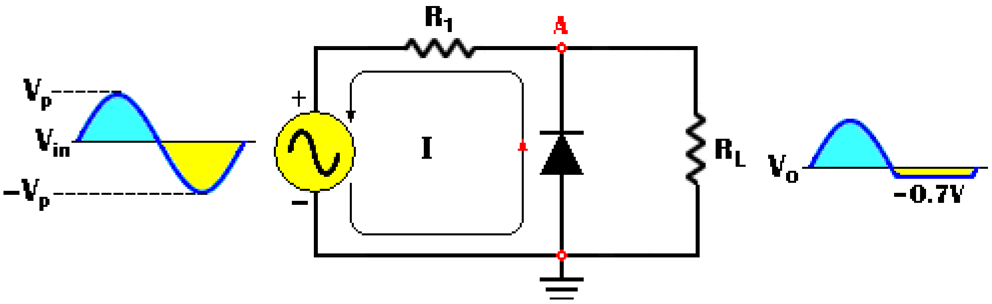


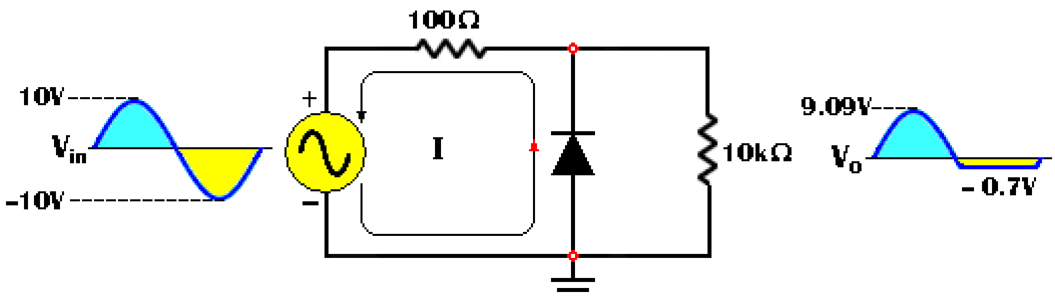
Figure 18: Circuit for the negative clipper

Example 10:

Determine the output voltage waveform to the circuit shown in figure below?

Solution:

The diode is forward biased and conduct when the input voltage goes below −0.7V the peak output voltage across R_L determine as follow:



$$V_{pout} = \left(\frac{R_L}{R_L + R_1}\right) V_{pin} = \frac{10 \times 10^3}{100 + 10 \times 10^3} \times 10 = 9.09V$$

Positive biased clippers:

The level to which an ac voltage is limited can be adjusted by adding a bias voltage V_B, in series with the diode, as shown figure 19.

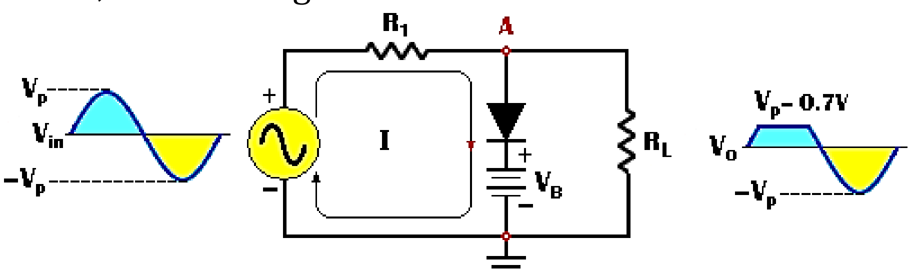


Figure 19: Positive biased clipper

The voltage at point **A** is equal to $(V_B + 0.7V)$ before the diode will become forward biased and conduct.

Once the diode begins to conduct, the voltage at point **A** is limited to $(V_B + 0.7V)$so that all input voltage abovethis level is clipped off.

Negative biased clippers:

To obtain negative biased clipper circuit, the diode and bias voltage must connect as shown in figure 20. In this case, the voltage at point A must go below $(-V_B - 0.7V)$ to forward bias the diode an initiate limiting action as shown.

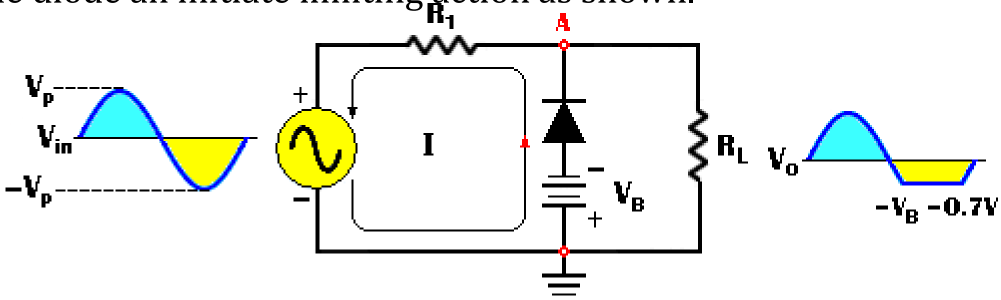


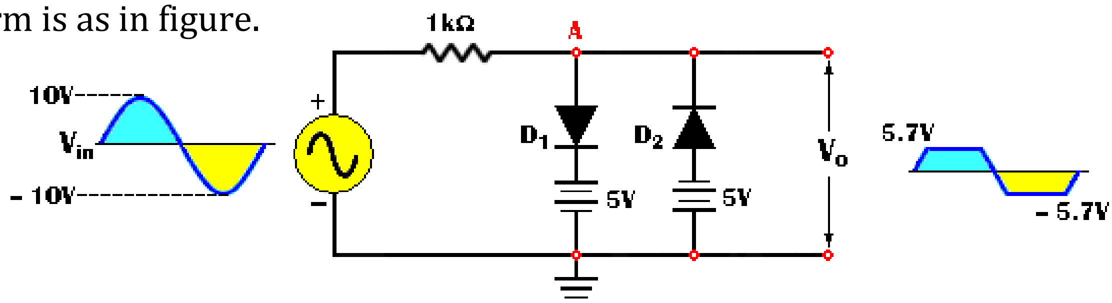
Figure 20: Negative biased clipper

Example 11:

Figure below shows a circuit combining a positive clipper with a negative clipper. Determine the output voltage waveform?

Solution:

When the voltage at point **A** reaches +5.7V, diode D_1 conducts and limits the waveform to +5.7V. Diode D_2 does not conduct until the voltage reaches −5.7V. Therefore positive voltage above +5.7V and negative voltage below−5.7V are clipped off. Output voltage waveform is as in figure.



2. Diode Clampers:

A clamper adds a dc level to an ac voltage. Clampers are sometimes known as dc **restorers**.

Positive clamper:

Figure22 shows a diode clamper that inserts a positive dc level in the output waveform. The operation can be seen by considering the first negative half cycle for input voltage, when input voltage initially goes negative, the diode is forward biased allowing the capacitor to charge near the peak of the input $(V_p - 0.7V)$. Just above the negative peak the diode is reverse biased. This is because the diode cathode is held near the$(V_p - 0.7V)$ by charge on the capacitor

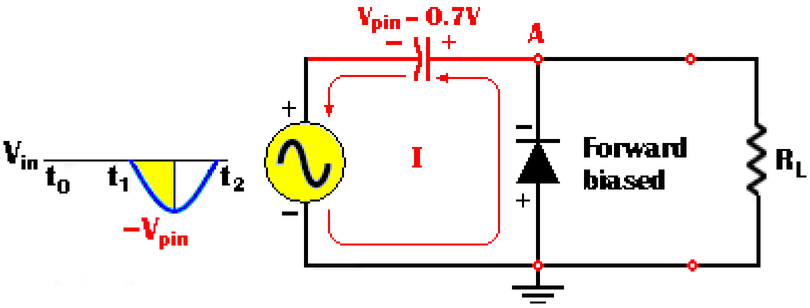


Figure 22: Positive clamper operation

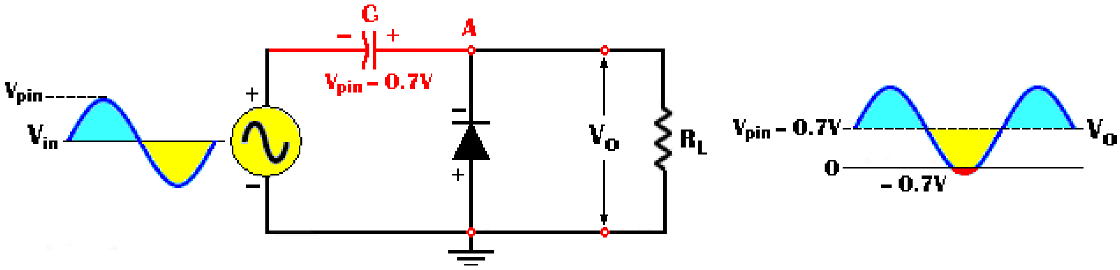


Figure 23: Positive clamper

The capacitor can only discharge through the high resistance R_L. The net effect of the clamping action is that the capacitor retains a charge approximately equal to the peak value of the input less the diode dropV_D, as shown in figure 23.The capacitor voltage acts essentially as a battery in series with input signal.

Negative clamper:

The negative clamper achieved by turn the diode, as in figure 24.The capacitor voltage reverses and circuit becomes a negative clamper. The clamping is less than perfect because the positive peak has a reference level of 0.7V instead of 0V.

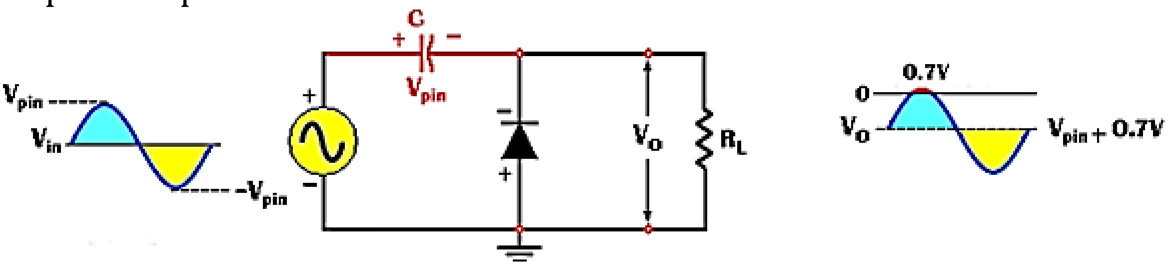


Figure 24: Negative clamper

Example 12:

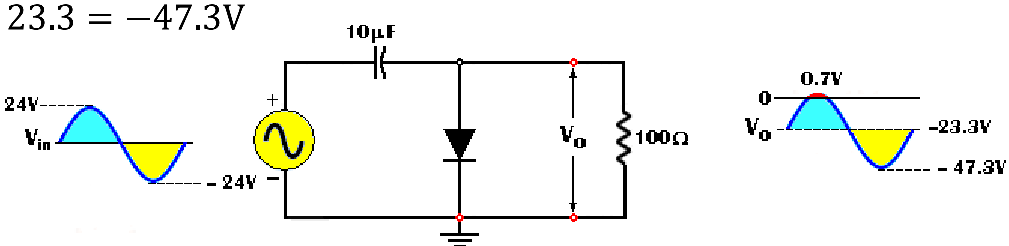
What is V_o that you would expect to observe across R_L in the clamper circuit?

Solution:

Negative dc value equal to the input peak less the diode drop V_D.

$$V_{dc} = -\left(V_p - V_D\right) = -(24 - 0.7) = -23.3V$$

$$V_{out} = -24 - 23.3 = -47.3V$$



6. ZENER DIODES:

The zener diode is designed for operation in the reverse breakdown region. The breakdown voltage of a zener diode is set by carefully controlling the doping level during manufacture. $(I - V)$ characteristic in figure1 shows that when a diode reaches reverse breakdown, its voltage remains almost constant even though the current changes drastically, and this is true in normal operating regions for rectifier diodes and for zener diode shown as shaded areas. If a zener diode is forward biased, it operates as rectifier diode and as a clipper circuit.

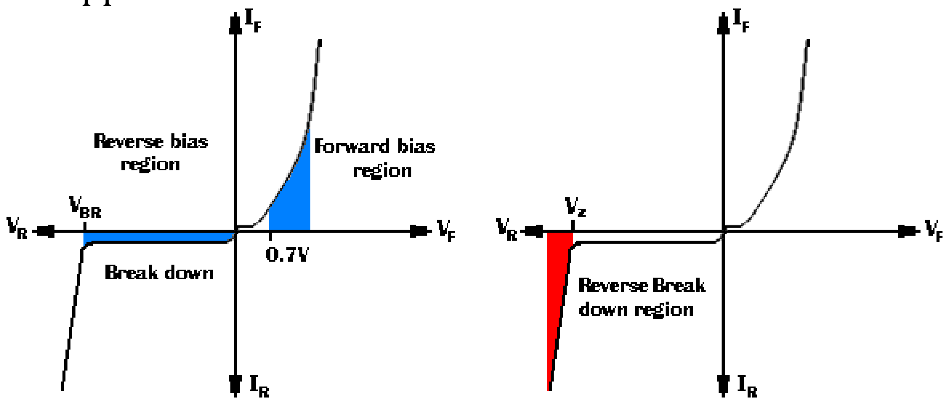


Figure 1: normal operating regions for rectifier diode and for zener diode shown as shaded areas

1. Zener Breakdown:

Two types of reverse breakdown in a zener diode are **avalanche** and **zener**.

•The avalanche occurs in rectifier and zener diode at sufficiently high reverse voltage.

•Zener breakdown occurs in zener diode at sufficiently low reverse voltages.

A zener diode 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 V_Z, the field is intense enough to pull electrons from their valance bands and create a current.

2. Breakdown Characteristic:

From figure2, we observe that, when the reverse voltage V_R, is increased, the reverse current I_R remains small up to "knee" of the curve. the reverse current is also called the zener current I_Z.

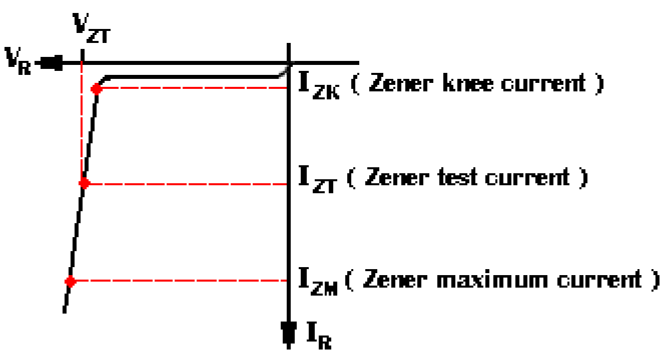


Figure 2: Reverse characteristic of zener diode.

At "knee" point the breakdown effect begins; the internal zener resistance r_Z, begins to decrease as the reverse current increases rapidly. From the bottom of the knee the zener breakdown voltage V_Z, remains essentially constant although it increases slightly as the zener current I_Z increases.

3. Zener Equivalent Circuit:

Figure 3a shows the practical model of a zener diode. Where the zener resistor is include. Since the actual voltage curve is not ideally vertical, a change in zener current(ΔI_Z) produce a small change in zener voltage ΔV_Z, figure 3b, so r_Z is as in following equation:

$$r_Z = \frac{\Delta V_Z}{\Delta I_Z}$$

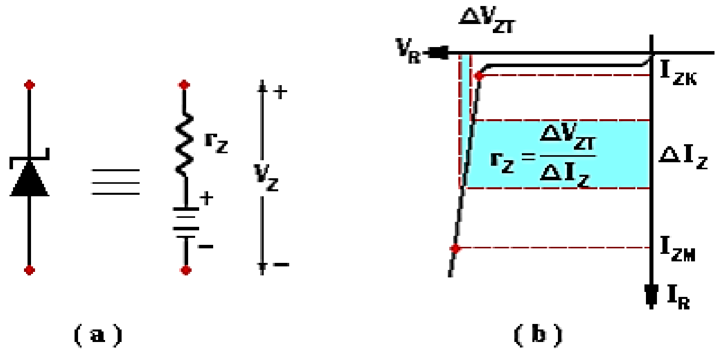


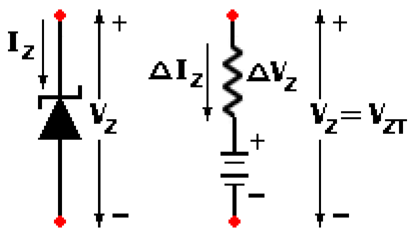
Figure 3: Zener diode equivalent circuit models and characteristic curve illustrating r_Z.

In most cases, you can assume that r_Z is constant over the full linear range of zener current values and is purely resistive.

Example 13:

Zener diode has $r_Z = 3.5\Omega$. The data sheet gives $V_{ZT} = 6.8V$ at $I_{ZT} = 37mA$ and $I_{ZK} = 1mA$. What is the voltage across the zener terminals when the current is 50mA, and then 25mA?

Solution:



For $I_Z = 50mA$;

$\Delta I_Z = I_Z - I_{ZT} = 50 - 37 = 13mA$

I_Z is a 13mA increase above $I_{ZT} = 37mA$.

$\Delta V_Z = \Delta I_Z \times r_Z = 13 \times 3.5 = 45.5mV$

The change in zener voltage when I_Z becomes 50mA is:

$V_Z = 6.8 + \Delta V_Z = 6.8V + 45.5mV = 6.85V$

For $I_Z = 25mA$;

$\Delta I_Z = I_Z - I_{ZT} = 25 - 37 = -12mA$

I_Z is a 12mA decrease below $I_{ZT} = 37mA$.

$\Delta V_Z = \Delta I_Z \times r_Z = -12 \times 3.5 = -42mV$

The change in zener voltage when I_Z becomes 25mA is:

$V_Z = 6.8 + \Delta V_Z = 6.8v - 42mv = 6.76V.$

4. Zener Regulation:

The ability to keep the reverse voltage across its terminals essentially constant is the voltage regulator because it maintains (حافظ) a nearly constant voltage across its terminals over a specified (محدد) range of reverse current values.

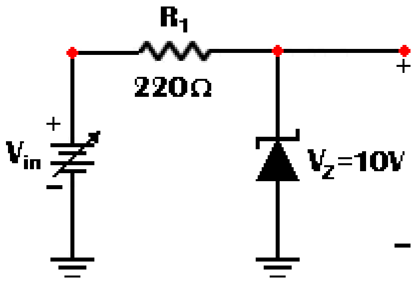
Zener regulation with a varying input voltage:

When V_{in} change, I_Z will change proportionally so that the limitations of the input voltage variation are set by the minimum and maximum current values with which the zener diode can operate($I_{ZK} < I_Z < I_{ZM}$).

Example 14:

Determine the minimum and maximum input voltage that can be regulated by the zener diode in figure below? (note: $I_{ZK} = 0.25mA$ and $I_{ZM} = 100mA$).

Solution:



- For the minimum zener current the voltage across R_1 is:

  $V_{R_1} = I_{ZK} \times R_1 = 0.25mA \times 220\Omega = 55mV.$

  $V_{R_1} = V_{in} - V_Z$

  $V_{inmin} = V_{R_1} + V_Z = 55mv + 10v = 10.055V$

- For the maximum zener current the voltage across R_1 is:

  $V_{R_1} = I_{ZM} \times R_1 = 100mA \times 220\Omega = 22V.$

  $V_{R_1} = V_{in} - V_Z$

  $V_{inmax} = V_{R_1} + V_Z = 22V + 10v = 32V$

This zener diode can regulate the input voltage from 10.055V to 32V and maintain an approximate 10V output.

Zener regulation with a variable load:

The zener diode maintains a nearly constant voltage across variable load resistor R_L as long as the zener current is ($I_{ZK} < I_Z < I_{ZM}$), as shown in figure 4:

- When load resistor is open circuit ($R_L = \infty$), the load current is zero ($I_L = 0$) and all current is passing in the zener; this is no load condition.

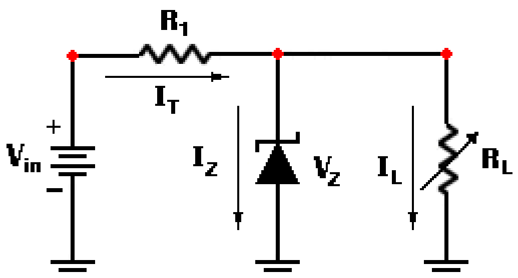


Figure 4: zener regulation with a variable load

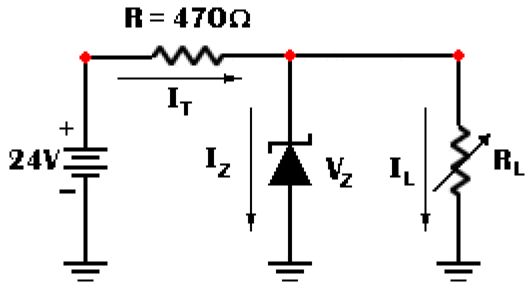
- When the load resistor R_L is connected, part of the total current is through the zener and part through R_L.The total currentI_T through R_1 remains constant as long as the zener is regulating. As R_L is decreased, the load current I_L increase and I_Z decreases.

The zener diode still to regulate the voltage until I_Z reaches its minimum value I_{ZK}. At this point the load current I_L is maximum and a full load condition exists.

Example 15:

Determine the minimum and maximum load current I_L for which the zener diode in figure below will maintain regulation. What is the minimum value of R_L that can be used? (note: $V_Z = 12v, I_{ZK} = 1mA$ and $I_{ZM} = 50mA$ assume $r_Z = 0$).

Solution:



When $I_L(\text{min}) = 0A$ $(R_L = \infty), I_Z$ is maximum and equal to the total current I_T.

$$I_Z(\text{max}) = I_T = \frac{V_{in} - V_Z}{R} = \frac{24 - 12}{470} = 25.5mA$$

$I_Z(\text{max}) < I_{ZM}$

0A is an acceptable minimum value for I_L because the zener can handle all of the 25.5mA. The maximum value of I_L occurs when $I_Z$is minimum $(I_Z = I_{ZK})$, so:

$$I_L(\text{max}) = I_T - I_{ZK} = 25.5 - 1 = 24.5mA$$

The minimum value of R_L is:

$$R_L(\text{min}) = \frac{V_Z}{I_L(\text{max})} = \frac{12}{24.5} = 490\Omega$$

That is mean regulation is maintained for any value of $R_L$between 490Ω and ∞.

Example 16:

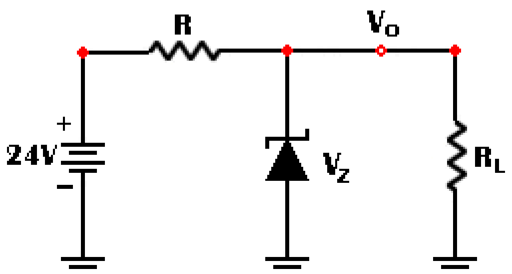
The zener diode used in the regulator circuit of figure below has $V_{ZT} = 15V$ at I_{ZT}, $I_{ZK} = 0.25mA, I_{ZT} = 17mA$, the power dissipation $P_D = 1w$ and $r_Z = 14\Omega$.

a) Determine V_{out} at I_{ZK} and I_{ZM}?

b) Calculate the value of R that should be used?

c) Determine the minimum value of R_L that can be used?

Solution:



a) For I_{ZK}:

$$V_{out} = V_Z = 15 - \Delta I_Z \times r_Z$$

$$V_{out} = 15 - (I_{ZT} - I_{ZK}) \times r_Z$$

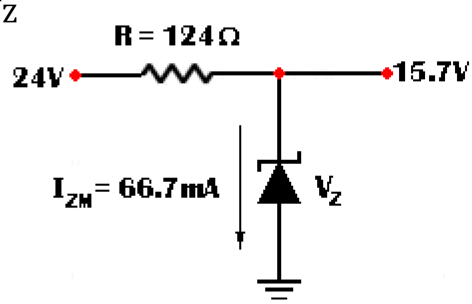
$$V_{out} = 15 - (17 - 0.25) \times 14 = 14.76V$$

For I_{ZM}:

$$I_{ZM} = \frac{P_D}{V_Z} = \frac{1}{15} = 66.7\text{mA}$$

$$V_{out} = V_Z = 15 - \Delta I_Z \times r_Z = 15 - (I_{ZT} - I_{ZM}) \times r_Z$$

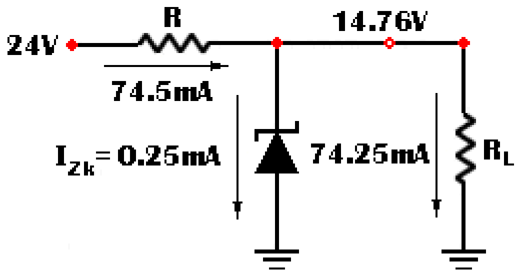
$$V_{out} = 15 - (17 - 66.7) \times 14 = 15.7\text{V}$$



b) The maximum zener current that occurs when there is no load as in figure below:

$$R = \frac{V_{in} - V_Z}{I_{ZM}} = \frac{24 - 15.7}{66.7} = 124\Omega$$

c) For the minimum load resistance R_L (maximum load current), the zener current is minimum ($I_{ZK} = 0.25\text{mA}$) as in figure below:



$$I_T = \frac{V_{in} - V_{out}}{R} = \frac{24 - 14.76}{124} = 74.5\text{mA}$$

$$I_L = I_T - I_{ZK} = 74.5 - 0.25 = 74.25\text{mA}$$

$$\therefore \text{minimum } R_L = \frac{V_{out}}{I_L} = \frac{14.76}{74.25} \approx 200\Omega$$

PHYSICAL

2024

Chapter Three

Electrical properties in semiconductors .

Semiconductors Physics for First Class
Systems and Control Department

Chapter Three: Electrical properties in Semiconductor.

3.1 Electrical Connectivity

In semiconductor, the conduction band electron and valence band hole participate in electrical conduction. To obtain expression for electrical conductivity consider an intrinsic semiconductor bar which is connected to external battery as shown in Fig. 2.1.

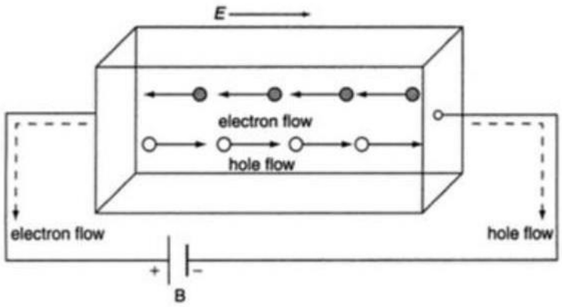


Fig. 2.1 Semiconductor bar connected to the battery.

The electric field exist along x direction. The field accelerate electrons (conduction electrons) along negative x direction. They starts moving with a constant velocity called **Drift velocity (v_d)** .

The drift velocity produced per unit electric field is called **mobility (μ)** , Thus :

$$\mu = v_d \ / \ \varepsilon$$

or

$$v_d = \mu \, \varepsilon \qquad \ldots\ldots(2.1)$$

The unit of mobility (μ) is (m^2/volt.sec).

- **Drift Current Density (J_d):**

Drift current is the electric current, or movement of charge carriers, which is due to the applied electric field. When an electric field is applied across a semiconductor material, a current is produced due to the flow of charge carriers.

In order to find the current density of electrons, let the concentration of electrons are 'n', charge is 'e' and drift velocity is 'v_d' , then :

$$J_d = n\, e\, v_d \qquad \text{……(2.2)}$$

Substituting eqn. (2.1) of drift velocity in eqn. (2.2), we can write:

$$J_d = n\, e\, \mu\, \mathcal{E} \qquad \text{……(2.3)}$$

Also the drift current density (J_d) is the amount of current per unit area:

$$J_d = I/A \qquad \text{……(2.4)}$$

Where :
I : the current passing through the semiconductor.
A : is across-section area in (meter).

- **Conductivity (σ) :**

Conductivity is a measure of its ability to conduct electricity. Calculated as the ratio of the current density in the material to the electric field which causes the flow of current (Ohms law).

From Ohms law :

$$J_d = \sigma\, \mathcal{E} \qquad \text{…..(2.5)}$$

From eqn. (2.3) and eqn. (2.5), we can write:

$$J_d = \sigma\, \mathcal{E} = n\, e\, \mu\, \mathcal{E}$$

Then :

$$\sigma = n\, e\, \mu \qquad \text{……(2.6)}$$

The unit of conductivity (σ) is Siemens per meter (S/m).

The **conductivity (σ)** is inversed proportional to the **Resistivity (ρ)** :

$\sigma \;\alpha\; 1/\rho$

Example:

A silicon crystal having a cross-sectional area of 0.001cm^2 and a length of 10^{-3}cm is connected at it s ends with 10v battery at temperature 300^{o}K, when the current is 100mA. Find the resistivity and the conductivity?

Solution:

$$J = \sigma E \Rightarrow \sigma = \frac{J}{E} = \frac{I/A}{V/L} = \frac{100\times10^{-2}/0.001\times10^{-4}}{10/(10^{-3}\times10^{-2})} = 10\,(\Omega.m)^{-1}$$

$$\rho = \frac{1}{\sigma} = \frac{1}{10} = 0.1(\Omega.m)$$

Example:

1μA current passing through an intrinsic silicon bar has 3mm length and 50$\times$ 100 μm^2 cross-section. The resistivity of the bar is 2.3×10^5 $\Omega.cm$ at 300^{o}K. find the voltage across the bar?

Solution:

$J = \sigma E$, $J = I / A$, $\sigma = 1/\rho$

$I / A = (1/\rho) * E$

$E = (I * \rho) / A$

$= (1 * 10^{-6} * 2.3 * 10^5 * 10^{-2}) / (50 * 10^{-6} * 100 * 10^{-6})$

$= 4.6 * 10^5$ V / m .

$V = E * L$

$= 4.6 * 10^5 * 3 * 10^{-3} = 1380$ V .

Example:

Given (1.8×10^{-8} Ω.m) is the resistively for a copper bar with length (2cm). The applied voltage on this bar is (10 V) and the conduction electron density is (8.5×10^{28} m^{-3}). Find the mobility and drift velocity?

Solution:

$\sigma = ne\mu = 1/\rho \Rightarrow \mu = 1/ne\rho$

$\mu = 1/(8.5\times10^{28}\times1.6\times10^{-19}\times1.8\times10^{-8}) = 4.08\times10^{-3}\ m^2/V.s$

3.2 Electrical Properties in Semiconductors

A fundemental difference between a metal and a semiconductor is that the former is unipolar (conducte current by means of charges (electrons) of one sign only), whereas a semiconductor is bipolar (contains two charge carrying "particles" of opposite sign).

3.2.1 Electrical Conduction in Intrinsic Semiconductors

Conductivity one carrier is negative (the free electron), of mobility μ_n , and the other is positive (the hole), of mobility μ_p. These particles move in opposite directions in an electric field Ɛ, but since they are of opposite sign, the current of each is in the same direction.

$\sigma = n\,e\,\mu$ for Conduction

$\sigma_i = \sigma_n + \sigma_p$ for Intrinsic Semiconductor

$= n\,e\,\mu_n + p\,e\,\mu_p$

$\because n = p = n_i$

$\therefore \sigma_i = n_i\,e\,(\mu_n + \mu_p)$

3.2.2 Electrical Conduction in Extrinsic Semiconductors

In **n-type Semiconductor** , the semiconductor is doped by impurities has N_D oncentration ($n \gg p$) and ($n = N_D$) then the conductivity is:

$$\sigma_{(n)} = \sigma_n + \sigma_p$$

$$= N_D\, e\, \mu_n + p\, e\, \mu_p \qquad \ldots\ldots(2.11)$$

In **p-type Semiconductor** , the semiconductor is doped by impurities has N_A oncentration ($p \gg n$) ($p = N_A$) then the conductivity will be:

$$\sigma_{(p)} = \sigma_n + \sigma_p$$

$$= n\, e\, \mu_n + N_A\, e\, \mu_p \qquad \ldots\ldots(2.12)$$

Ex) Pure germanium has 4×10^{22} $atom/cm^3$ *doped by indium atoms,*

*the impurity is add to the extent of **1** part in* 10^8 *germanium atoms, if the intrinsic concentration of germanium* $2.5 \times 10^{13} cm^{-3}$*, note that* $\mu_n = 3800 \frac{cm^2}{v.s}$ *and* $\mu_p = 1800 \frac{cm^2}{v.s}$.

1) *Find the conductivity and the resistivity before the doping?*
2) *Find the conductivity and the resistivity after the doping?*
3) *What you conclude from 1 and 2?*

Sol:

1) $\sigma_i = \sigma_n + \sigma_p$

$$\sigma_i = ne\mu_n + pe\mu_p$$

$\because$ *the semiconductor is intrinsic* $\longrightarrow$ $n = p = n_i$

$$\sigma_i = n_i \times e(\mu_n + \mu_p)$$

$$\sigma_i = 2.5 \times 10^{13} \times 1.6 \times 10^{-19} (3800 + 1800) = 0.0224 \ s/cm$$

$$\rho_i = \frac{1}{\sigma_i} = \frac{1}{0.0224} = 44.64 \ \Omega.cm$$

2) *Doping with Indium means adding acceptor atoms:*

$$\therefore N_A = \frac{4 \times 10^{22}}{10^8} = 4 \times 10^{14} cm^{-3}$$

$$n \times p = n_i^2 \quad \longrightarrow \quad n \times N_A = n_i^2 \quad \longrightarrow \quad n = \frac{n_i^2}{N_A}$$

$$n = \frac{(2.5 \times 10^{13})^2}{4 \times 10^{14}} = 1.56 \times 10^{12} cm^{-3}$$

$$\sigma_{(p)} = \sigma_n + \sigma_p$$

$$\sigma_{(p)} = ne\mu_n + N_A e\mu_p$$

$$_{(p)} = 1.6 \times 10^{-19}(1.56 \times 10^{12} \times 3800 + 4 \times 10^{14} \times 1800)$$

$$= 0.116\, s/cm$$

$$\rho = \frac{1}{\sigma_{(p)}} = \frac{1}{0.116} = 8.62\ \Omega.c$$

3.3 Diffusion Current Density (J_{diff}) in Semiconductor

It is possible to have a nonuniform concentration of particles in a semiconductor. As indicated in Fig. 2.8, the concentration p of holes varies with distance x in the semiconductor, and there exists a concentration gradient $\frac{dp}{dx}$ in the density of carriers. The existence of a gradient implies that if an imaginary surface (shown dashed) is drown in the semiconductor, the density of holes immediately on one side of the surface is larger than the density on the other side. The holes are in a random motion as a result of their thermal energy. Accordingly, holes will continue to move back and forth across this surface. We may then expect that, in a given time interval, more holes will cross the surface from the side of greater concentration to the side of smaller concentration than in the reverse direction. This net transport of holes across the surface constitutes a current in the positive *x* direction. It should be noted that this net transport of charge is not the result of mutual repulsion among charges of like sign, but is simply the result of a statistical phenomenon. This diffusion is exactly analogous to that which occurs in a neutral gas if a concentration gradient exists in the gaseous container. The diffusion hole current density J_p (ampere per square meter) is proportional to the concentration gradient, and is given by:

$J_{p\ diff} = -e\ D_p\ dp/dx$

Where

$D_p = K\ T/\ e * \mu_p$

$V_T = KT/e = T/11600$

Where k is the Boltzmann constant in joules per degree Kelvin.

$k = 1.38 * 10^{-23}$ (J / K) , $k = 8.617 * 10^{-5}$ eV/K .

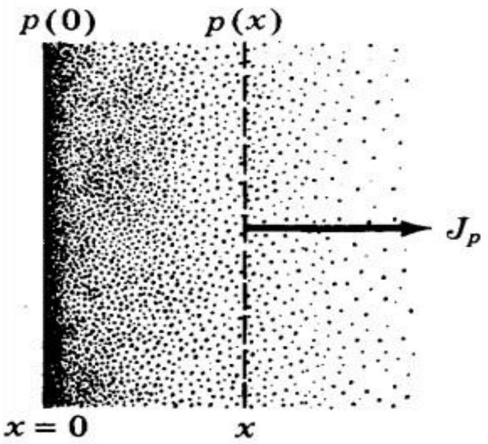


Fig. 2.8 A non-uniform concentration p(x) results in a diffusion current J_{pdiff}.

Where D_p (square meters per second) is called the diffusion constantfor holes. Since *p* in Fig. 2.8 decreases with increasing *x*, then *dp/dx* is

negative and the minus sign in eqn. (2.13) is needed, so that J_p will be positive in the positive *x* direction.

A similar equation exists for **diffusion electron current density** [*p* is replaced by **n**, and the minus sign is replaced by a **plus sign** in eqn.(2.13)] `and is given by:

$J_{n\ diff} = eD_n\ dn/dx$

Where

$D_n = KT/e * \mu_n$

$V_T = KT/e = T/11600$

Example (H.W): The relationship of changing the density of electrons along the x-axis is given as [1028 exp(−10−6𝑥)]. Find the diffusion current density at (x=0) and (x=10-5 m) if the mobility of electron is (4 x10-3 m2 /V.s) at T=3000 K? e = 1.6x10-19C , K = 1.38x10-23J/K.

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Chapter Three complete :

Electronic physics for first class

3.4 P-N Junction in Equilibrium (Zero Bias)

In a p – n junction, without an externally applied voltage, an equilibrium condition is reached in which a potential difference forms across the junction. This potential difference is called built-in potential V_D .

Consider the special case indicated in Fig. 2.1. The left half of the bar is *p-type* with a constant concentration N_A, whereas the right half is *n-type* with a uniform density N_D. The dashed plane is a metallurgical (p-n) junction separating the two sections with different concentrations. This type of doping, where the density changes abruptly from *p-* to *n-type* , is called step grading. The step-graded junction is located at the plane where the concentration is zero.

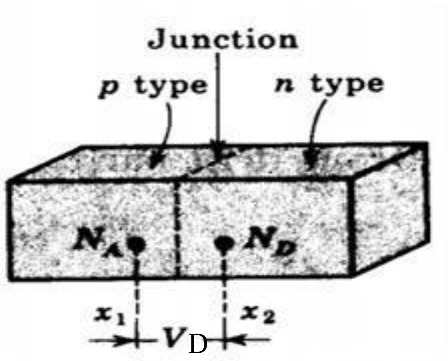


Fig. 2.1 Zero Bias PN Junction.

$$V_D = V_{21} = V_T \ln \frac{p_p}{p_n}$$

$$where \quad p_p = N_A \qquad and \qquad p_n = \frac{{n_i}^2}{N_D}$$

$$V_D = V_T \quad \ln \frac{N_A\, N_D}{{n_i}^2}$$

$V_T = KT/e = T/11600$

If donor impurites are introduced into one side and acceptors into the other side of a single crystal of a semiconductor, a *p-n* junction is formed, as in Fig. 2.1. Such a system is illustrated in more schematic detail in Fig. 2.2 . The donor ion is represented by a plus sign because, after this impurity atom "donates" an electron, it becomes a positive ion. The acceptor ion is indicated by a minus sign because, after this atom "accepts" an electron, it becomes a negative ion. Initially, there are nominally only *p-type* carriers to the left of the junction and only *n-type* carriers to the right.

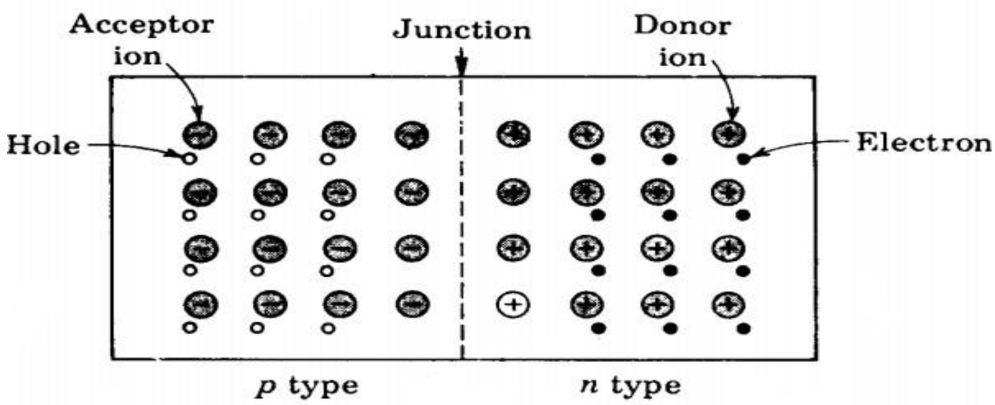


Fig. 2.2 A schematic diagram of PN junction.

The region of the junction is depleted of mobile charges, it is called the *depletion region*, the *space charge region,* or the *transition region*.

The thickness of this region is of the order of the wavelength of visible light (0.5 micron = 0.5μm). Within this very narrow space charge layer there are no mobile carriers. To the left of this region the carrier concentration is $p=N_A$ and to its right it is n= N_D.

The space charge density is zero at the junction. It is positive to the right and negative to the left of the junction.

The two terminal device (called a junction diode), as shown in Fig. 2.3, is a device that conducts current in only one direction.

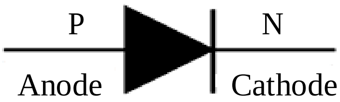


Fig. 2.3 Diode schematic symbol.

3.5 P-N Junction Bias

If the external potential of **V volt** is applied across the P-N junction this will bias the diode. There are two types of diode bias:

3.5.1 Forward Bias

Forward Bias An external voltage applied with the polarity shown in Fig. 2.4. Where Connecting the positive terminal of the external voltage source to the p-side and the negative terminal to the n-side will cause a forward bias for the junction

The application of **Forward Bias** potential **V** will cause an injection of electrons from the n-side and a hole from the p-side in opposite directions across the junction region and some of these carriers will recombine with the ions near the boundary region and reduce the width of the depletion region.

On being injected across the junction, these carriers immediately become minority carriers.

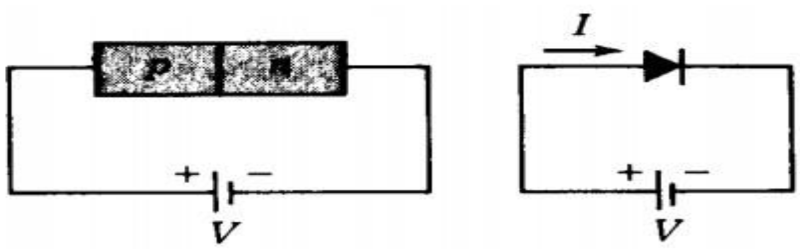


Fig 2.4 P-N Junction biased in the forward direction.

3.5.2 Reverse Bias

Reverse Bias If the positive terminal of the applied voltage connect to the n-type and the negative terminal to p-type, as shown in Fig. 2.5, the junction will bias in reverse direction. The depletion region has been winded, that result to overcome the region from the majority carrier more and more carriers.

The current in reverse-bias condition called **Reverse Saturation Current (I_S).**

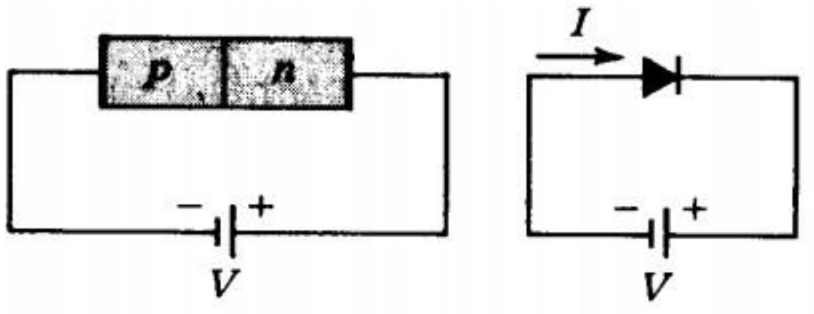


Fig 2.5 P-N Junction biased in the reverse direction.

Example 1:

A PN junction was formed from two pieces of silicon contain $N_D = 10^{24} m^{-3}$ and $N_A = 10^{20} m^{-3}$ at 300°K. Calculate the built in potential of the p-n junction where $n_i = 1.45 \times 10^{16} m^{-3}$.

Sol:

$$V_D = \frac{kT}{e} \ln \frac{N_D N_A}{n_i^2}$$

$$= \frac{1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}} \ln \frac{10^{24} \times 10^{20}}{(1.45 \times 10^{16})^2} = 0.7 \text{ volt}$$

Example 2:

The conductivity of n-side in the Ge PN junction is $10^4\ s/m$ and for the p-side is $10^2\ s/m$. Find the built in potential for the junction at 300°K? where $n_i = 2.5 \times 10^{19} m^{-3}$, $\mu_n = 0.36\ m^2/v.s$ and $\mu_p = 0.16\ m^2/v.s.$

sol:

At n-side:

$$\sigma_{(n)} = n_n\, e\, \mu_n + p_n\, e\, \mu_p = N_D\, e\, \mu_n + \frac{n^2}{N_D} e\, \mu_p$$

$$10^4 = 1.6 \times 10^{-19} (0.36\, N_D + \frac{(2.5 \times 10^{19})^2}{N_D} \times 0.16)$$

$$N_D = 1.7 \times 10^{23} m^{-3}$$

At p-side:

$$\sigma_{(p)} = p_p e \mu_p + n_p e \mu_n = N_A\, e\, \mu_p + \frac{n_i^2}{N_A} e\, \mu_n$$

$$10^2 = 1.6 \times 10^{-19} (0.16\, N_A + \frac{(2.5 \times 10^{19})^2}{N_A} \times 0.36)$$

$$N_A = 3.9 \times 10^{21} m^{-3}$$

$$V_D = \frac{kT}{e} \ln \frac{N_D N_A}{n_i^2}$$

$$= \frac{1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}} \ln \frac{1.7 \times 10^{23} \times 3.9 \times 10^{21}}{(2.5 \times 10^{19})^2}$$

$$= 0.36 \text{volt}$$

3.6 The Volt - Ampere Characteristics of Diode

The relationship between the current that passed through the diode and the voltage applied at its ends is exponential relationship, where the expression for the diode current **I** is :

$$I = I_S\,\left(^{\frac{V}{y\,V_T}} - 1\right) \qquad \ldots\ldots.(2.1)$$

$$I = I_S\, e^{\frac{V}{y\,V_T}} - I_S$$

Where : V : the applied voltage.

V_T : the volt equivalent of temperature and is given by :

$V_T = T / 11600 = KT/e$.

At room temperature ($T = 300^o$ K) , $V_T = 0.026$ V = 26 mV.

I_s : Reverse saturation current.

η : constant , for Ge = 1 , Si = 2 .

The form of Volt -Ampere characteristic described by eqn. (2.1) is shown in Fig. 2.6.

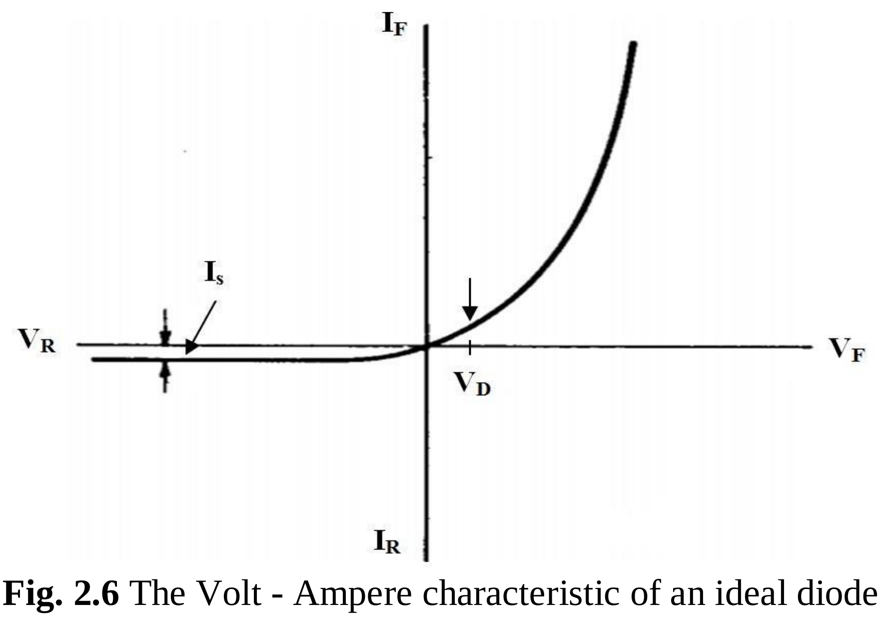


Fig. 2.6 The Volt - Ampere characteristic of an ideal diode.

When the diode is **Reverse Biased** and V is several times V_T , then $\mathbf{I \approx I_s}$ as shown in the left side of Fig. 2.6 . The reverse current is therefore constant , independent of the applied reverse bias.

In **Forward Bias**, the current beyond the **V_D (Cut in or Threshold voltage)** is rises very rapidly, as shown in the right side of Fig. 2.6.

V_D is approximately 0.3 V for Ge and 0.7 for Si.

In forward bias, eqn. (2.1) can be written as :

$$I_F = I_s\ e^{\frac{V}{y\, V_T}} \qquad \dots\dots..(2.2)$$

Example 3:

A silicon PN junction has a hole density in p-side 10^{24}m^{-3} and electron density in n-side 10^{22}m^{-3}, the mobility of the holes is $0.2\ \text{m}^2/\text{v. s}$ and the mobility of the electrons is $0.4\ \text{m}^2/\text{v. s}$. If the reverse saturation current equal to 0.04μ A and $n_i = 10^{19}\text{m}^{-3}$ at 17° C. Determine:

1) The density of majority and minority carriers and the conductivity?
2) The barrier potential?
3) The junction current when $V_F = 0.25\text{v}$?
4) The junction current for the reverse bias, at high reverse voltage?

Sol:

1) $\underline{\boldsymbol{At}\ \text{p} - \text{side}}$

$$n_p = \frac{n_i^2}{p_p} = \frac{(10^{19})^2}{10^{24}} = 10^{14}\text{m}^{-3}\ \text{electrons minority}$$

$N_A = 10^{24}\text{m}^{-3}$ holes majority

$$\sigma_p = e\, p_p\, \mu_p = 1.6 \times 10^{-19} \times 10^{24} \times 0.2 = 3.2 \times 10^{4}\ \text{s/m}$$

$$\sigma_n = e\, n_p\, \mu_n = 1.6 * 10^{-19} * 10^{14} * 0.4$$

$$\sigma_{(p)} = \sigma_p + \sigma_n$$

***At* n − side**

$p_n = \frac{n_i^2}{n_n} = \frac{(10^{19})^2}{10^{22}} = 10^{16} m^{-3}$holes minority

$N_D = 10^{22} m^{-3}$ electrons majority

$\sigma_n = e n_n \mu_n = 1.6 \times 10^{-19} \times 10^{22} \times 0.4 = 640\ s/m$

$\sigma_p = e p_n \mu_p$

$\sigma_{(n)} = \sigma_p + \sigma_n$

2) $V_D = \frac{kT}{e} \ln \frac{N_D N_A}{n_i^2} = \frac{1}{40} \ln \frac{10^{22} \times 10^{24}}{(10^{19})^2} = 0.46$ volt.

3) $I = I_S \left[\exp\left(\frac{V}{\eta\, v_T}\right) - 1\right]$

$V_T = \frac{T}{11600} = \frac{17+273}{11600} = 0.025$

$I = 0.04 \times 10^{-6} \left[\exp\left(\frac{0.25}{2 * 0.025}\right) - 1\right]$

4) At high reverse voltage:

$I_R = I_S = 0.04\ \mu A.$

CHAPTER 4
THE DIODES

4.1THE DIODE MODELS:

The Ideal Diode Model:

The ideal model of a diode is a simple switch.

- When the diode is forward biased, it acts like closed **(on)** switch, as in Figure1a.
- When the diode is reversed biased. it acts like an open **(off)** switch, as in Figure1b.

The barrier potential, the forward dynamic resistance, and the reverse current are all neglected.

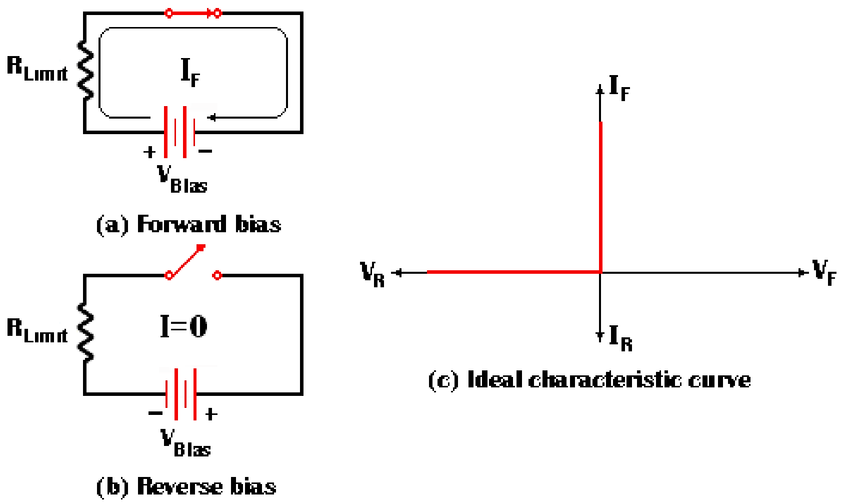


Figure 1: The ideal model of a diode

In Figure1c, the ideal I—V characteristic curve graphically depicts the ideal diode operation.

- The diode is assumed to have a zero voltage across it when forward biased ($V_F = 0V$).
- The forward current is find by the bias voltage and the limiting resistor using Ohm's law:

$$I_F = \frac{V_{bias}}{R_{limt}}$$

- The reverse current is neglected, as in Figure1c ($I_R = 0A$). The reverse voltage equals to the bias voltage ($V_R = V_{bias}$).

The Practical Diode Model:

The practical model adds the barrier potential to the ideal switch model.

- When the diode is forward biased, it is equivalent to a closed switch in series with a small equivalent voltage source equal to the barrier potential (0.7V) with the positive side toward the anode, as in Figure 2a. This equivalent voltage source represents the fixed voltage drop V_F produced across the forward biased pn junction of the diode and is not an active source of voltage.
- When the diode is reversed biased. It is equivalent to an open switch just as in the ideal model, as in Figure 2b. The barrier potential does not affect reverse bias. So it is not a factor.
- The characteristic curve for the practical diode model is in Figure2c.

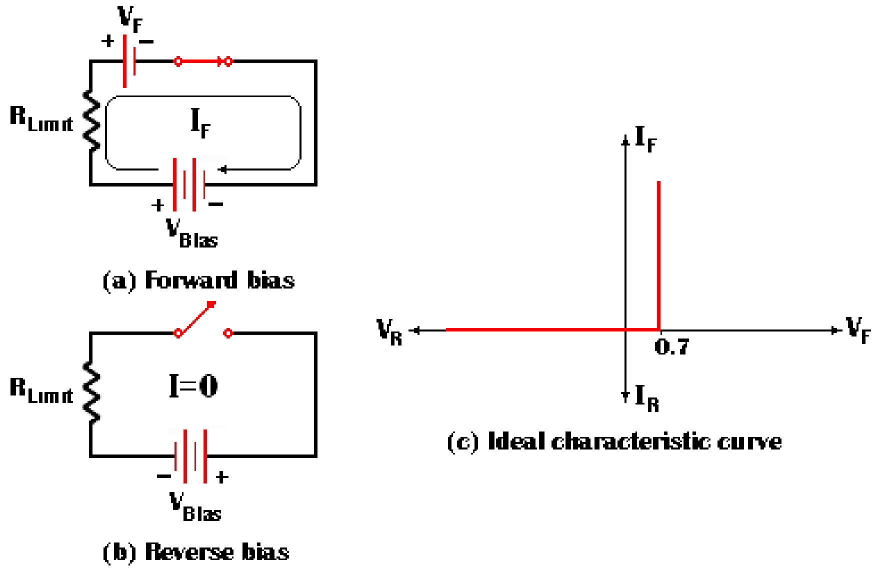


Figure 2: The practical model of a diode

- Since the barrier potential is included and the dynamic resistance is neglected, the diode is assumed to have a voltage across it when forward biased, as indicated by the portion of the curve to the right of the origin.

$$V_F = 0.7V$$

- The forward current is determined as follows by first applying KVL to Figure 2a:

$$V_{Bias} - V_F - V_{R_{limit}} = 0$$

$$V_{R_{limit}} = I_F \times R_{Limit}$$

Substituting and solving for I_F:

$$I_F = \frac{V_{Bias} - V_F}{R_{Limit}}$$

- The diode is assumed to have zero reverse current, as indicated by the portion of the curve on the negative horizontal axis.

$I_R = 0A$
$V_R = V_{Bias}$

The Complete Diode Model:

The complete model of a diode consists of the barrier potential, the small forward dynamic resistance (r_d), and the large internal reverse resistance (r_R). The reverse resistance is taken into account because it provides a path for the reverse current, which is included in this diode model.

- When the diode is forward biased, it acts as a closed switch in series with the barrier potential voltage and the small forward dynamic resistance (r_d), as in Figure3a.
- When the diode is reverse biased, it acts as an open switch in parallel with the large internal reverse resistance (r_R), as in Figure 3b. The barrier potential does not affect reverse bias, so it is not a factor.
- The characteristic curve for the complete diode model as in Figure3c. Since the barrier potential and (r_d) are included, the diode is assumed to have a voltage across it when forward biased.

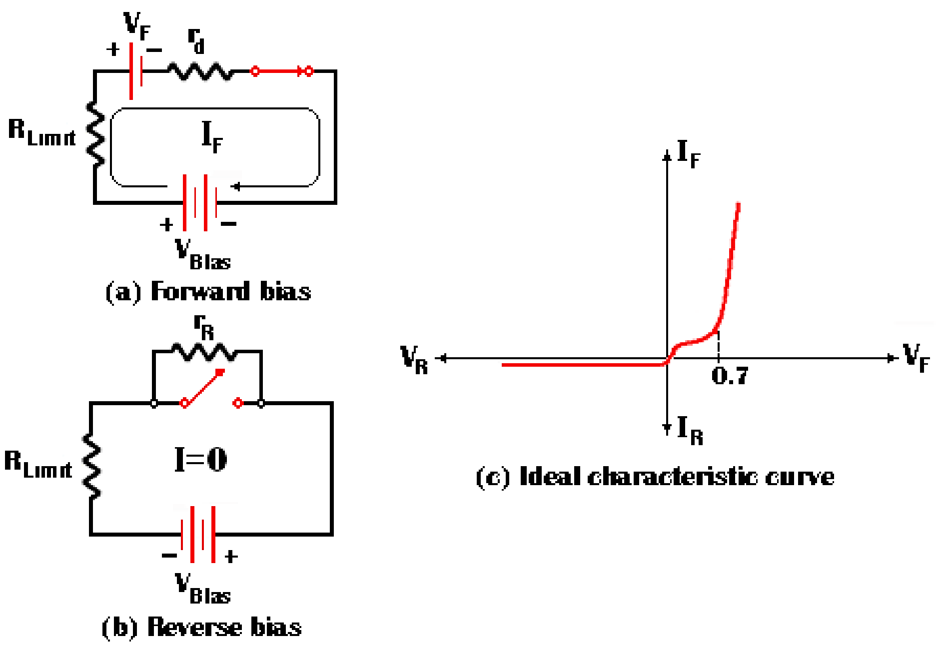


Figure 3: The complete model of a diode

- The voltage (V_F) consists of the barrier potential voltage plus the small voltage drop across (r_d), as indicated by the portion of the curve to the right of the origin. The curve slopes because the voltage drops due to dynamic (r_d) as the current increases. For the complete model of a silicon diode, the following formulas apply:

  $V_F = 0.7V + I_F \times r_d$

$$I_F = \frac{V_{Bias} - 0.7V}{R_{Limit} + r_d}$$

- The reverse current is taken into account with the parallel resistance and is indicated by the portion of the curve to the left of the origin.

Example 1:

a. Determine V_F and I_F for the diode in Figure (a) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume $r_d = 10\Omega$.

b. Determine V_R and I_R for the diode in Figure (b) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume $I_R = 1\mu A$.

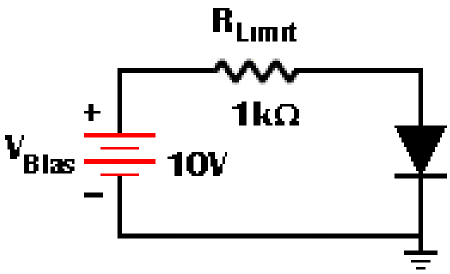
Solution:

a) Ideal model:

$V_F = 0V$

$$I_F = \frac{V_{bias}}{R_{limt}} = \frac{10}{1k\Omega} = 10mA$$

$V_{R_{limit}} = I_F \times R_{Limit} = 10mA \times 1k\Omega = 10V$



(a)

Practical model:

$V_F = 0.7V$

$$I_F = \frac{V_{Bias} - V_F}{R_{Limit}} = \frac{10V - 0.7V}{1k\Omega} = 9.3mA$$

$V_{R_{limit}} = I_F \times R_{Limit} = 9.3mA \times 1k\Omega = 9.3V$

Complete model:

$$I_F = \frac{V_{Bias} - 0.7V}{R_{Limit} + r_d} = \frac{10V - 0.7V}{1k\Omega + 10\Omega} = 9.21mA$$

$V_F = 0.7V + I_F \times r_d = 0.7V + 9.21mA \times 10\Omega = 792mV$

$V_{R_{limit}} = I_F \times R_{Limit} = 9.21mA \times 1k\Omega = 9.21V$

b) Ideal model:

$I_R = 0A$

$V_R = V_{Bias} = 5V$

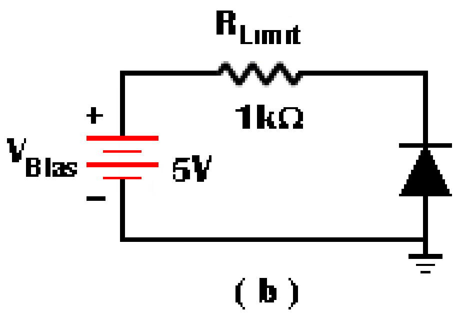
$V_{R_{limit}} = 0V$

Practical model:

$I_R = 0A$

$V_R = V_{Bias} = 5V$

$V_{R_{limit}} = 0V$



Complete model:

$I_R = 1\mu A$

$V_{R_{limit}} = I_R \times R_{Limit} = 1\mu A \times 1k\Omega = 1mV$

$V_R = V_{Bias} - V_{R_{limit}} = 5V - 1mV = 4.999V$

4.2 THE DIODE APPLICATIONS:

4.2.1 HALF WAVE RECTIFIER:

Figure 4, illustrates the half wave rectification. A diode is connected to an ac source and to a load resistor R_L forming a halfwave rectifier.

- When the sinusoidal input voltage (V_{in}) goes positive, the diode is forwardbiased and conducts current through R_L, as in Figure 4a. The current produces an output voltage across R_L which has the same shape as the positive halfcycle of the input voltage.

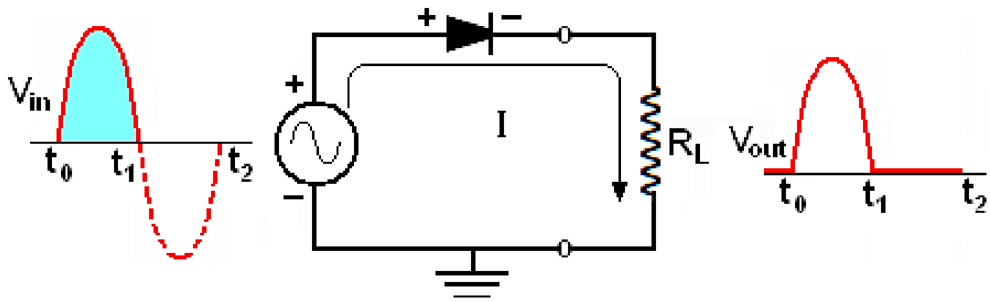


Figure 4a: During the positive alternation of the input voltage.

- When the input voltage goes negative during the second half of its cycle. The diode is reverse biased. There is no current, so the voltage across the load resistor is 0V, as in Figure 4b.

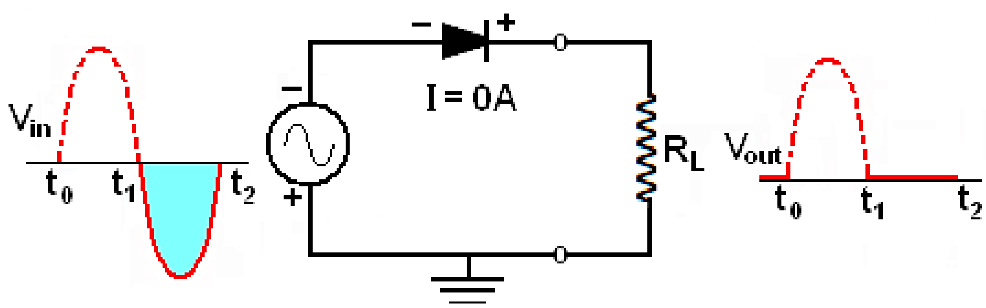


Figure 4b: During the negative alternation of the input voltage.

- The net result is that only the positive half cycles of the ac input voltage appear across the load. Since the output does not change polarity, it is a pulsating dc voltage with a frequency of 60 Hz, as in Figure 4c.

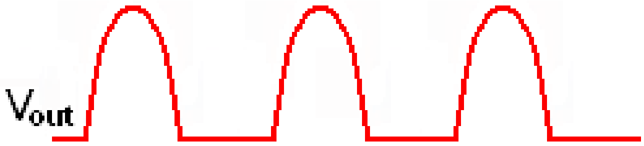


Figure 4c: 60 Hz half-wave output voltage for three input cycles

Average value of the half wave output voltage:

Mean the value which measured by a dc voltmeter. Mathematically, it is determined by finding the area under the curve over a full cycle, as in Figure 5. And then dividing by 2π, the number of radians in a full cycle, where V_p is the peak value of the voltage. This equation shows that V_{avg} is 31.8 % of V_p for a half wave rectified voltage.

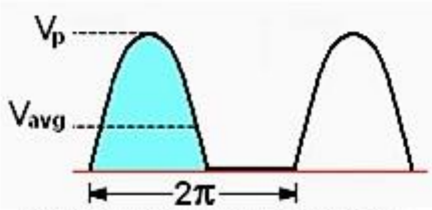


Figure5: Average value of the half wave rectified signal

$v = V_p \sin\theta\, d\theta$

$$V_{avg} = \frac{area}{2\pi} = \frac{V_p}{2\pi}\int_0^{\pi} \sin\theta d\theta = \frac{V_p}{2\pi}[\ -\cos\theta]_0^{\pi}$$

$$V_{avg} = \frac{V_p}{2\pi}[(-\cos\pi) - (-\cos 0)]$$

$$V_{avg} = \frac{V_p}{2\pi}[-(-1) - (-1)] = \frac{V_p}{2\pi} \times 2$$

$$V_{avg} = \frac{V_p}{\pi} \qquad \square \qquad V_{avg} = 31.8\% V_p$$

Example 2:

Determine is the V_{avg} of the half wave rectified voltage in Figure 5, if $V_p = 50V$?

Solution:

$$V_{avg} = \frac{V_p}{\pi} = \frac{50}{\pi} = 15.9V$$

Notice that V_{avg} is 31.8 % of V_p

Effect Of Barrier Potential On The Half Wave Rectifier:

When the practical diode model is used with the barrier potential of 0.7V taken into account, this is what happens. During the positive half cycle, the input voltage must overcome the barrier potential before the diode becomes forward biased. This results in a half wave output with a peak value that is 0.7V less than the peak value of the input, as in Figure 6.

$V_{p(out)} = V_{p(in)} - 0.7V$

Voltage is to reduce the peak value of the input by about 0.7V.

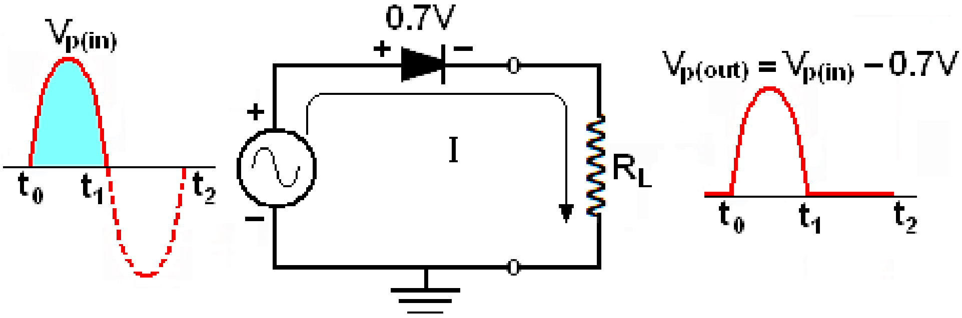


Figure 6: The effect of the barrier potential on the half wave rectified output

Example 3:

Determine$V_{p(out)}$ of the rectifier in Figure 6, if the input voltage is:

a) $V_{P(in)} = 5V$?

b) $V_{P(in)} = 100V$?

Solution:

a) $V_{p(out)} = V_{p(in)} - 0.7V = 5 - 0.7 = 4.3V$

b) $V_{p(out)} = V_{p(in)} - 0.7V = 100 - 0.7 = 99.3V$

The barrier potential could have been neglected, with very little error (0.7 %). But if it is neglected in circuit (a), a significant error results (14 %).

Half wave Rectifier with Transformer Coupled Input voltage:

A transformer is often used to couple the ac input voltage from the source to the rectifier, as in Figure 8. two advantages provides from the coupling:

1) It allows the source voltage to be stepped up /down as needed.
2) The ac source is electrically isolated from the rectifier, thus preventing a shock hazard in the secondary circuit.

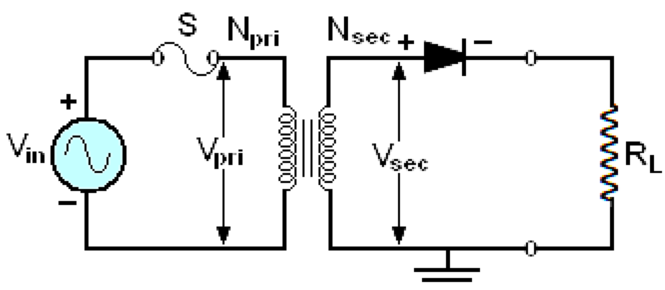


Figure 8: Half wave rectifier with transformer coupled input voltage.

The turn's ratio **(n)** is equal to the ratio of secondary turns ($N_{seconary}$)to the primary turns ($N_{primary}$) :

$$n = \frac{N_{seconary}}{N_{primary}}$$

$$V_{seconary} = n \times V_{primary}$$

- $n > 1$, the secondary voltage is greater than the primary voltage.
- $n < 1$, the secondary voltage is less than the primary voltage.

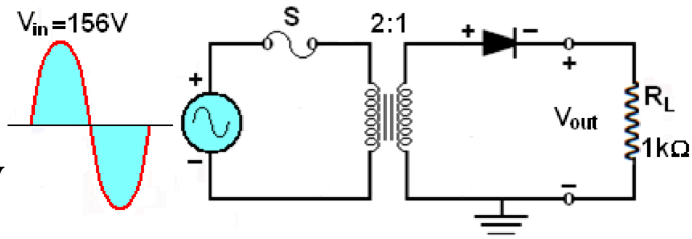
The peak secondary voltage, $V_{p(seconary)}$ in a transformer coupled half wave rectifier is equal to $V_{p(in)}$. Therefore:

$$V_{p(out)} = V_{p(seconary)} - 0.7V$$

Example 4:

Determine the peak value of the output voltage of the circuit below?

Solution:



$V_{p(pri)} = V_{p(in)} = 156V$

The peak secondary voltage is:

$V_{p(sec)} = nV_{p(pri)} = 0.5 \times 156V = 78V$

The rectified peak output voltage is:

$V_{p(out)} = V_{p(sec)} - 0.7V = 78 - 0.7 = 77.3V$

Where $V_{p(sec)}$ is the input to the rectifier.

4.2.2 FULL WAVE RECTIFIER:

Is the most commonly used type in dc power supplies. The result of full wave rectification is an output voltage with a frequency twice the input frequency that pulsates every half cycle of the input, as in Figure 9.

The average value, which is the value measured on a dc voltmeter, for a full wave rectified sinusoidal voltage is twice that of the half wave, as shown in the following formula:

$$V_{avg} = \frac{2V_p}{\pi} \quad \square \quad V_{avg} = 63.7\%V_p$$

V_{avg}:is approximately 63.7% of V_p for a full wave rectified voltage.

The center tapped full wave rectifier:

A center tapped rectifier use **two diodes** connected to the secondary of a center tapped transformer, as in Figure 9. The input voltage is coupled through the transformer to the center tapped secondary. Half of the total secondary voltage appears between the center tap and each end of the secondary winding as shown.

- For a positive half cycle of the input voltage, the polarities of the secondary voltages are as in Figure 10a. This condition forward biases diode $\mathbf{D_1}$ and reverse biases diode $\mathbf{D_2}$. The current path is through $\mathbf{D_1}$ and the load resistor $\mathbf{R_L}$ as indicated.

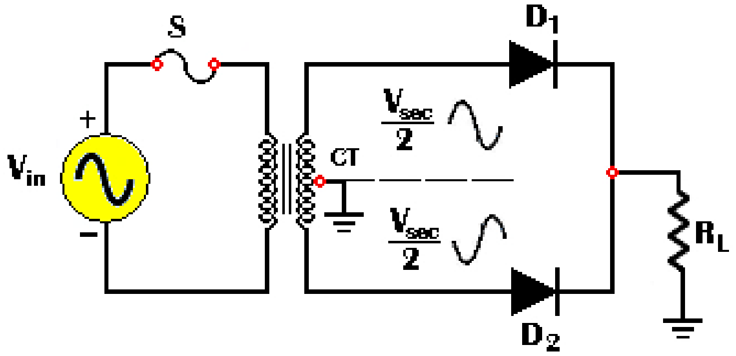
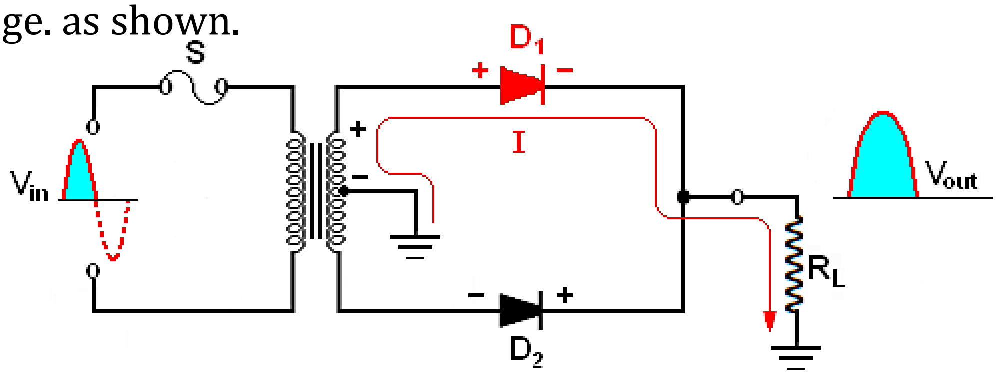
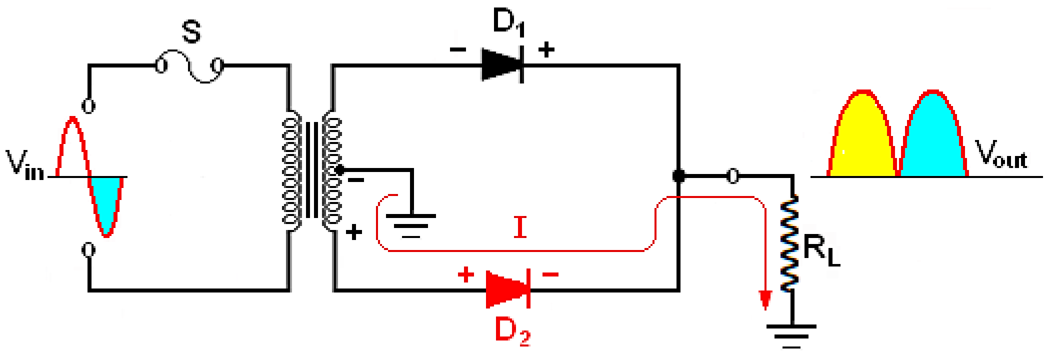


Figure 9: A center-tapped full-wave rectifier.

- For a negative half cycle of the input voltage, the voltage polarities on the secondary are as shown in figure10b. This condition reverse biases $\mathbf{D_1}$ and forward biases $\mathbf{D_2}$. The current path is through $\mathbf{D_2}$ and $\mathbf{R_L}$ as indicated. Because the output current during through the load, the output voltage developed across the load resistor is a full wave rectified dc voltage. as shown.



a) During positive half cycles, D_1 is forward biased and D_2 is reverse biased.



b) During negative half cycles. D_2 is forward-biased and D_1 is reverse biased.

Figure10:Basic operation of a center tapped full wave rectifier

Effect of the turns ratio on the output voltage:

- If the transformer's turns ratio is (n = 1):

  The voltage across each half of the secondary is equal to:

$$V_{p(sec)} = \frac{V_{p(pri)}}{2}$$

$$V_{out} = \frac{V_{p(pri)}}{2} - 0.7V$$

- If the transformer's turns ratio is (n = 2):

  The voltage across each half of the secondary is equal to:

$$V_{p(sec)} = V_{p(pri)}$$

$$V_{out} = V_{p(pri)} - 0.7V$$

The output voltage of a center tapped full wave rectifier is always one half of the **total secondary** voltage less the diode drop, no matter what the turns ratio.

$$V_{out} = \frac{V_{sec}}{2} - 0.7V$$

Example 5:

Show the voltage waveforms across each half of the secondary winding and across R_L when a 100V peak sine wave is applied to the primary winding in figure below?

Solution:

The transformer turns ratio n = 0.5.

The total peak secondary voltage is :

$$V_{p(sec)} = nV_{p(pri)} = 0.5 \times 100 = 50V$$

There is a 25V peak across each half of the secondary with respect to ground. The output load voltage :

$$25 - 0.7 = 24.3V$$