UNIT 11 SEMICONDUCTOR DIODES

Structure

11.1 INTRODUCTION

We begin this Block with a study of semiconductor diodes and their applications. An ideal diode is a two-terminal device which offers zero resistance to current flow in one direction called the *forward direction* and infinite resistance to current flow in the opposite direction called *reverse direction.* It simulates a closed switch for current flow in the forward direction and an open switch if a voltage tends to drive a current in the reverse direction. Thus it is akin to a one-way valve in a fluidic system. The foregoing model is an idealization. A practical diode is essentially a nonlinear resistor offering a varying but low value of resistance to currents in the forward direction and a varying but high value of resistance to currents in the reverse direction. Vacuum tube diodes, which were in vogue in the early days of electronics have now become obsolete and the term diode is nowadays taken to refer to only a solid state diode made from semiconductor materials.

In this Unit, we first get acquainted with the mechanism of current conduction in solids and the distinguishing features of conductors and insulators. We then learn the meaning of p and n type semiconductors and get to know what happens in a pn-junction and how biasing the junction affects its conduction. The V - I characteristic of the junction diode and its idealization are then presented.

The diode is one of the widely used components in electronic circuits. You will learn, later on, that almost every electronic apparatus or instrument needs a d.c voltage for its operation. If we exclude portable units powered by d.c batteries, these units mostly work off a.c mains supply and therefore there is a need to convert the available a.c voltage to a suitable d.c voltage supply, a process referred to as *rectification.* The rectifier action constitutes the most important application of a diode and you will find diodes wherever you encounter rectifier circuits. This and other interesting applications of diodes constitute the rest of the coverage in this unit.

Objectives

After studying this unit, you should be able to

- understand the way a diode acts as an open circuit when reverse biased and acts as a short circuit when forward biased,
- solve circuit problems in which diodes are used, and
- use diodes in a variety of applications.

11.2 SEMICONDUCTORS

On the basis of their ability to conduct electricity, solids can be classified as metals (conductors), insulators and semi conductors. *Metals* are good conductors and offer little resistance to the flow of free charge carriers. *Insulators* are ones which offer high resistance to the flow of free charge carriers. In between these classes, there are elements which are neither good conductors nor good insulators. These are called *semiconductors.*

11.2.1 Conduction in Solids

Conduction in solids occurs due to free movement of charge carriers when subjected to an electric field. A conductor has a large number of free electrons in the crystal structure moving about at random. The number of electrons (free) does not increase much as temperature is increased. When an electric field is applied these electrons still moving about at random develop an average movement in the direction opposite to that of the electric field. As the movement of negative charges is in the direction opposite to that of the electric field, this constitutes a positive current in the direction of the electric field. The average velocity v with which these electrons move is directly proportional to the electric field, E.

Therefore $v = \mu_n E$ where μ_n is the mobility of electrons in the conductor.

The current density $J = n\, q\, v$ A/m^2 where n is the number of electrons per unit volume (number/m^3) and q is the electronic charge in coulombs.

$$J = n\, q\, \mu_n\, E \qquad (11.1)$$

or

$$J = \sigma E$$

where σ is the conductivity of the metal.

This is basically *Ohm's law.*

An insulator does not have any free charge carriers (or has very few charge carriers) in the crystal. Therefore its conductivity is very low.

11.2.2 Intrinsic Semiconductor

* A *hole* is created when an electron is dislodged from the crystal structure. A *hole* behaves like a free positive charge carrier (of strength q) and develops an average drift velocity in the direction of the applied field.

A semiconductor (intrinsic) has equal number of *free electrons* and *absence of electrons (called holes*)* constituting the charge carriers. Hence the current is the resultant combination of that due to electrons and that due to holes.

Therefore,

$$J = n_i\, q\, v_n + p_i\, q\, v_p$$

where n_i and p_i indicate intrinsic free electron and hole concentrations and v_n and v_p are the respective velocities of electrons and holes.

$$J = (n_i\, q\, \mu_n + p_i\, q\, \mu_p)\, E = \sigma E \qquad (11.2)$$

μ_n and μ_p being the electron and hole mobilities in the semiconductor.

11.2.3 Doped Semiconductor

A semiconductor belonging to the fourth group in the periodic table is silicon (Si). It has four valence electrons per atom. These are loosely bound to the parent atom in the crystal lattice. If one of these electrons becomes free it creates a vacancy known as *hole.* Both of these, the free electron and the hole, are free carriers which move at random in the crystal.

When a controlled quantity of impurity like a third group element (e.g., boron) which has only three valence electrons is added to the silicon it results in one free hole being contributed for every impurity atom added. This can result in the carriers becoming predominantly holes. These are called the majority carriers and electrons then become the minority carriers. This type of semiconductor is known as ***p*-type semiconductor.** The impurities are called acceptor type of impurities because the crystal can accept one electron in this bonding with the parent atoms and thereby contribute to a hole.

When impurities like aluminium (Al) belonging to the fifth group are added selectively to silicon (Si) each impurity atom having five valence electrons in trying to imitate the parent Si atoms contributes one excess electron as free electron to the crystal. This results in the majority carriers now becoming electrons and minority carriers in turn becoming holes. The semiconductor thus becomes ***n*-type**.

These semiconductors by themselves can be used as resistors. The resistance R of a semiconductor of length l and area of cross section A, is $R = l/\sigma A$ where σ is the conductivity. Its $V - I$ characteristic can be plotted as shown in Figure 11.1(a).

The inverse of the slope of the characteristic gives the resistance.

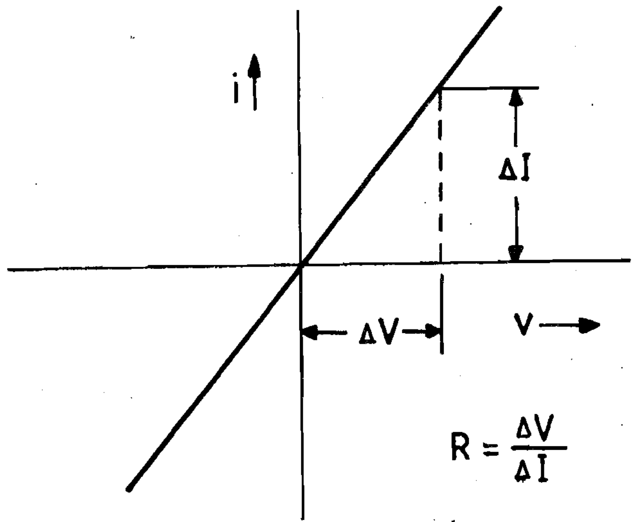


Figure 11.1 (a) : Linear Resistor, $R = \frac{l}{\sigma A}$

Thermistors are semiconductor resistors whose resistance variation with respect to temperature is very high. They are widely used in instrumentation as temperature transducers.

Example 11.1

Draw the $V - I$ characteristic of a resistance (linear) whose value is known to be 100 Ω.

Solution

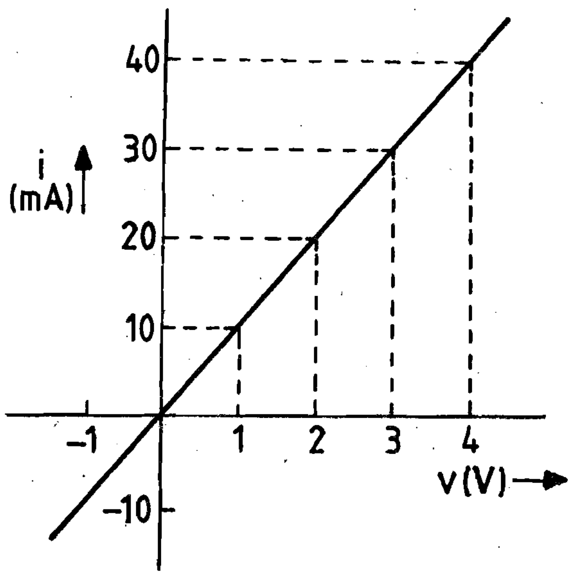


Figure 11.1 (b) : For Example 11.1

SAQ 1

Sketch the $V - I$ characteristic of a 1 kΩ resistor.

11.3 DIODES

11.3.1 Ideal Diode

An ideal diode has a $v - i$ characteristic as shown in Figure 11.2(a). The symbol for the diode is shown in Figure 11.2(b).

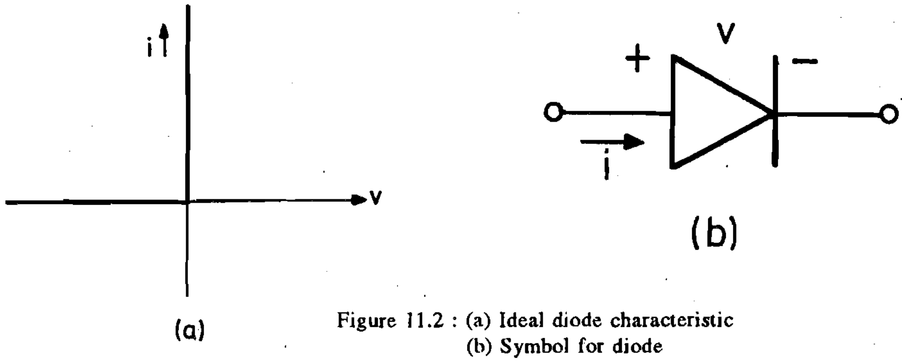


Figure 11.2 : (a) Ideal diode characteristic
(b) Symbol for diode

v and i are forward bias voltage and forward bias current respectively. The characteristic shown can be defined as : $i = 0$ for $v < 0$ and $v = 0$ for $i > 0$. The latter region is called the **forward biased region** and the former region is known as the **reverse biased region**. In terms of the extent of conduction, full conduction takes place in the forward region or the resistance is zero and conductance is zero in the reverse direction or there is complete resistance for the flow of current.

11.3.2 Ideal Semiconductor Diode

A junction formed between p and n type of semiconductors, termed as a $p - n$ junction, has a characteristic closely approximating that of the ideal diode of Figure 11.2(a). The functional relationship can be shown as

$$i = I_s\left[\exp\left(\frac{v}{\eta V_T}\right) - 1\right] \qquad (11.3)$$

This functional (exponential) relationship is shown in Figure 11.3.

Here I_s is known as the reverse saturation current because for $v < 0$ and $|v| > \eta V_T$

$$i \approx -I_s .$$

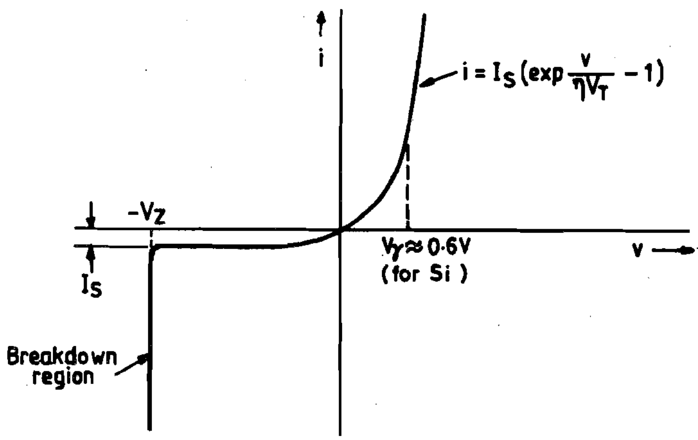


Figure 11.3 : v - i relation of a diode

V_T is known as the thermal voltage and is KT/q where K is the Boltzmann's constant, T is the absolute temperature and q is the electronic charge.

Then $$V_T = \frac{KT}{q} = 26 \text{ mV}$$

at room temperature of 27°C. η the correction factor lies between 1 and 2 accounting for the deviation from the simple diode theory which is due to Shockley.

In a practical semiconductor diode if the reverse bias voltage is increased, at a certain value of reverse bias voltage called breakdown voltage the current increases drastically for a small change in voltage (vide Figure 11.3). A diode commercially available for its use in the breakdown region is called the *Zener diode*. The breakdown voltage is termed V_z. Diodes used for working in the forward biased region and reverse biased region before breakdown are known as *rectifier diodes*.

Example 11.2

An ideal diode shown in Figure 11.4(a) is in series with a 1 kΩ resistor. A 5 V battery is applied to the network so as to forward bias the diode. Determine the current through the diode.

Solution

From the circuit of Figure 11.4 (a), we have

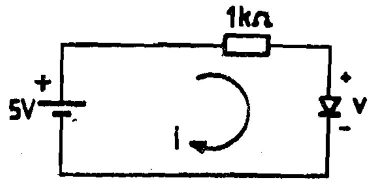


Figure 11.4 (a) : For Example 11.2

$5 = i \times 10^3 + v$.

As the diode is forward biased ($i > 0$), $v = 0$. Hence $i = 5$ mA.

It is instructive to obtain the result graphically. The operating point (defining the voltage and current of the diode) should lie on the ideal diode characteristic (Figure 11.2(a)) as well as the line (called the load line) depicting the relation $v = 5 - i \times 10^3$, forced by the circuit in which the diode is placed. Accordingly, the diode operating point is fixed by the intersection of the two characteristics as shown in Figure 11.4 (b). Such graphical procedures are useful when nonlinear diode characteristic like that in Figure 11.3 are involved.

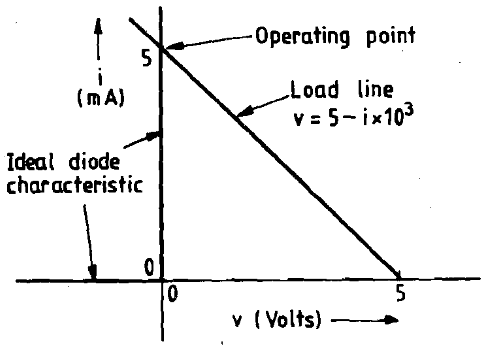


Figure 11.4 (b) : For solution to Example 11.2

Example 11.3

If a semiconductor diode is used in the same network of Example 11.2, determine i.

Solution

Again,

$$5 = i \times 10^3 + v \qquad (11.4)$$

But, $$i = I_S \left[\exp(v/\eta V_T) - 1\right] \qquad (11.5)$$

Therefore, $$v = \eta\, V_T \ln\left(1 + \frac{i}{I_S}\right) \qquad (11.6)$$

These two Eqs. (11.4) and (11.6) must be solved in order to arrive at the solution for i. It can be carried out this way.

Initially v can be assumed to be zero (ideal diode value); then i becomes 5 mA.

Then v can be evaluated using Eq. (11.6).

$$v = \eta\, V_T \ln\left(1 + \frac{5 \times 10^{-3}}{I_S}\right)$$

Use this value of v to calculate i from Eq. (11.4). This can be repeated until the value of i reached does not show much difference with the value earlier obtained at the previous step. An alternative approach is to use the graphical procedure suggested in Example 11.2.

SAQ 2

For $I_S = 100$ nA, $\eta = 1$, $V_T = 26$ mV, evaluate i and v of the diode in Example 11.3, using the iterative technique suggested therein.

11.4 APPLICATIONS

Diodes can be used for a variety of applications such as rectifiers, peak detectors, clippers, clampers, voltage multipliers, function generators, analogue gates, and logic gates.

We shall now have a brief look at these applications. In these applications, we will consider the diode to be ideal so as to simplify the treatment and the results obtained through such simplification are sufficiently realistic.

11.4.1 Rectifier

As already mentioned in the introduction, rectification is the process of converting an a.c. voltage to a d.c. voltage. Consider the circuit of Figure 11.5 (a). We desire to feed the load resistance R_L with a *unidirectional* d.c voltage from the available *bidirectional* a.c voltage.

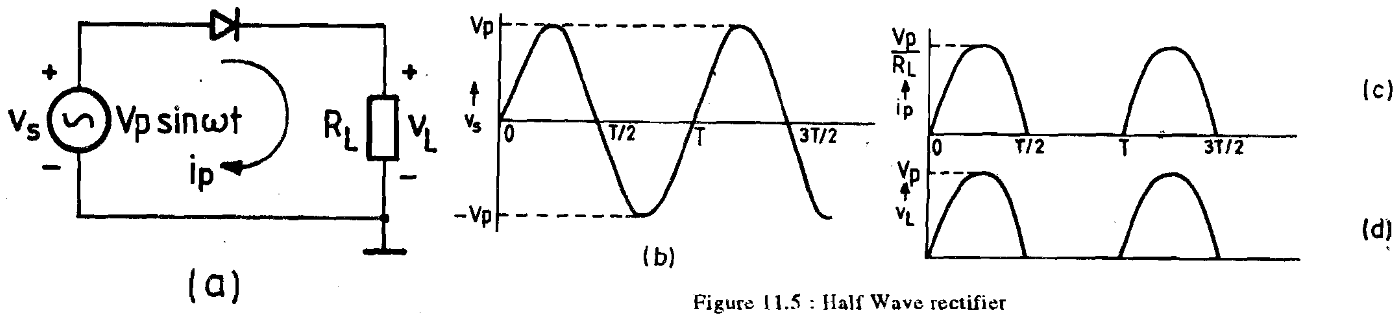


Figure 11.5 : Half Wave rectifier

For $V_p \sin wt > 0$, current can flow, $i_p = \frac{V_p}{R_L} \sin wt$ and $v_L = v_S$.

For $V_p \sin wt < 0$, $i_p = 0$ and $v_L = 0$, as the diode is reverse biased.

The resulting waveforms of the current and voltage at the load are sketched in Figures 11.5 (c) and (d). Note that the diode cuts off the negative half-cycles of v_S and allows only the positive half cycles of voltage to be impressed across the load. Hence this process is called **half wave rectification.**

SAQ 3

A halfwave rectifier has $R_L = 1$ kΩ and $v_S = 10 \sin 2\pi \times 50\, t$. Determine the load current and voltage waveforms.

Two diodes pumping currents into the common load R_L in alternative half cycles results in full wave rectification as shown in Figure 11.6(a).

Here i_1 equals $\frac{V_P \sin wt}{R_L}$ when $\sin wt > 0$ and is equal to zero otherwise. In contrast, i_2 equals $\frac{|V_P \sin wt|}{R_L}$ when $\sin wt < 0$ and is equal to zero otherwise. The load current i_L which equals $i_1 + i_2$ is then $\frac{|V_P \sin wt|}{R_L}$ for all t. As a unidirectional current exists in R_L for both half cycles of the input voltage, this is called **full wave rectification**.

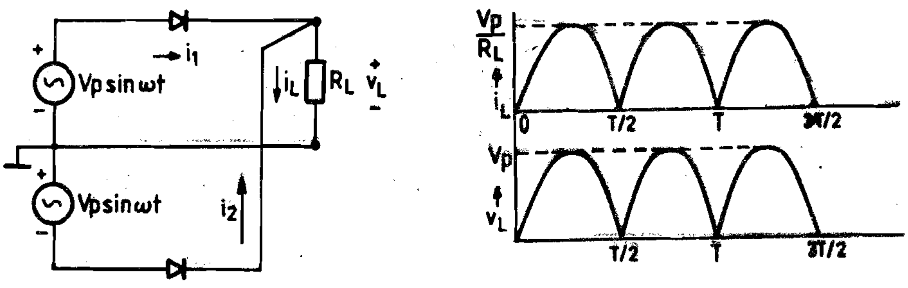


Figure 11.6 (a) : Full wave rectifier

Use of a transformer as shown Figure 11.6(b) gives the two out of phase voltages required for the arrangement of Figure 11.6(a) starting from a single input voltage $V_p \sin wt$.

Here a single phase transformer of turns ratio n : 2 with a centre tap on the secondary is used to give a recified voltage v_L having a peak of $(1/n)$ that of the primary input voltage.

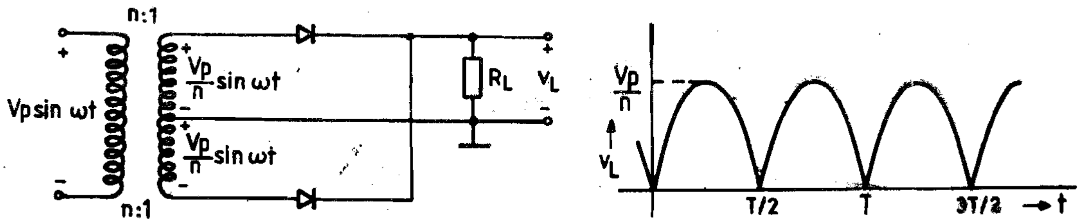


Figure 11.6 (b) : Full wave rectifier with a centre-tapped transformer

SAQ 4

A fullwave rectifier has a transformer with 10:2 turns ratio with a centre-tapped secondary and $v_S = 220\sqrt{2} \sin 2\pi \times 50t$, $R_L = 1$ kΩ. Sketch the waveform of voltage across the load resistance.

AC to DC Converters

The output voltages and currents of the rectifier circuits of Figures 11.5 and 11.6 are unidirectional but they do not have steady values as required of d.c quantities. To obtain reasonably steady values, filter circuits are used to smoothen the outut variation. A simple filter, comprising a shunt capacitor acting in a half-wave rectifier circuit is illustrated in the following.

In the circuit of Figure 11.7 (a), the capacitor gets charged to the peak value V_P of the input signal v_S at $t = T/2$ and thereafter retains this voltage as $v_{C1} = V_P > v_S$ and the diode blocks the discharge path. Thus the ac voltage $V_P \sin wt$ can be converted into a dc voltage across the capacitor but the voltage can not deliver any current into a load because it will

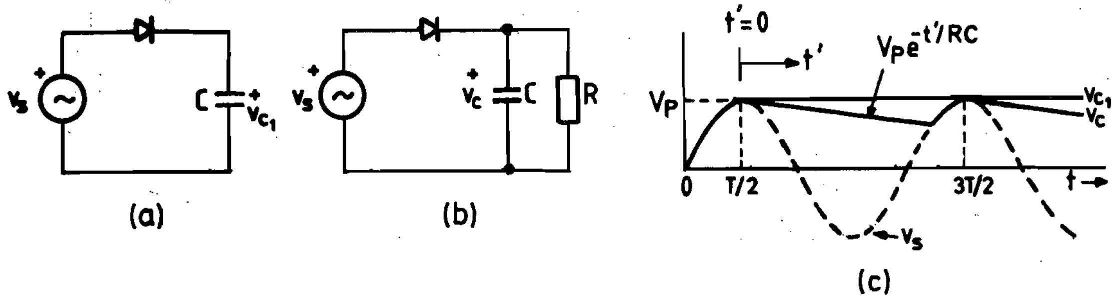


Figure 11.7 : AC to DC Converter Circuits
(a) AC to DC Converter without load (b) AC to DC Converter with load (c) Wave forms

discharge the capacitor. If the current of discharge is such that it loses very little of its charge then the latter can be replenished when it next gets connected to the input. Consider the circuit of Figure 11.7 (b), in which a load resistor R is connected across the capacitor. The voltage v_c across the capacitor during discharge is given by

$V_P \exp(-t'/RC)$ where $t' = t - T/2$. If t' is considered only in the region where $t'/RC << 1$, then

$$v_c = V_P \exp(-t'/RC) \approx V_P\left(1 - \frac{t'}{RC}\right)$$

Therefore if the capacitor gets charged to V_P, $V_P(1 - T/RC)$ would be approximately the smallest voltage on the discharge curve before charge gets replenished at $t' \approx T$ during the next positive cycle of the source voltage. If $T/RC << 1$ then v_c hardly changes from V_P, during the subsequent discharge and charge cycles after the initial charging to V_P.

We can therefore conclude that the d.c voltage and current of the load are given by

$$V_{dc} \approx \frac{1}{2} V_P \left[1 + 1 - \frac{T}{RC}\right] = V_P\left[1 - \frac{T}{2RC}\right] \approx V_P \text{ and } I_{dc} \approx V_P/R.$$

The output (load) voltage has a ripple with a peak to peak value,

$$\Delta v_c = \frac{V_P T}{RC} = \frac{I_{dc} T}{C}. \qquad (11.7)$$

Example 11.4

Design a half-wave rectifier circuit to obtain a d.c voltage of 15 V from 220 V, 50 Hz line voltage. If a capacitor of 2000 μF is employed and the d.c load current is 100 mA, determine the peak to peak value of the ripple in the output voltage.

Solution

A transformer with turns ratio n is required so that

$$V_{dc} = \frac{V_P}{n} = 15 \text{ V}$$

$$n = \frac{V_P}{15} = \frac{220\sqrt{2}}{15} = \frac{311}{15} = 20.733$$

It is given that the current required to be delivered is 100 mA or $R = 150\ \Omega$.

To satisfy the condition, $T/RC << 1$,

C must be much greater than $\dfrac{20 \times 10^{-3}}{150 \times 10^{-6}} = \dfrac{20000}{150}\ \mu\text{F} = 133.3\ \mu\text{F}$.

This condition is satisfied as $C = 2000\ \mu\text{F}$. The output voltage has therefore a peak to peak ripple $\Delta v_c = \dfrac{I_{dc}}{C} \times T$

$$= \frac{100 \times 10^{-3}}{2000 \times 10^{-6}} \times 20 \times 10^{-3} = 1 \text{ V}$$

Actual dc voltage $= 15 - 0.5 = 14.5$ V.

To obtain an actual dc voltage of 15 V, the transformer turns ratio can be reduced to (14.5/15) times the nominal value above i.e., make $n = 20.04$ or say 20.

The actual circuit is shown in Figure 11.8.

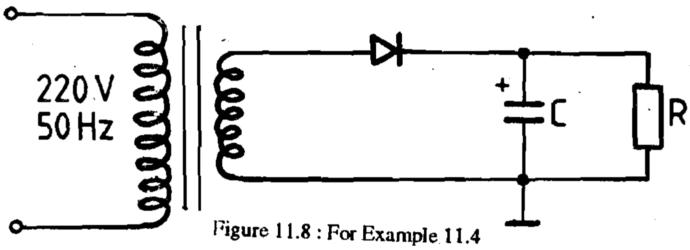


Figure 11.8 : For Example 11.4

11.4.2 Peak Detector

Consider the circuit of Figure 11.9.

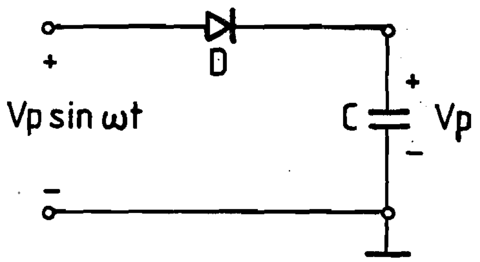


Figure 11.9 : Peak detector

If the capacitor C is initially uncharged, diode D would get forward biased when it starts charging the capacitor to input voltage until voltage across the capacitor reaches the peak V_p. Thereafter the capacitor voltage remains at V_p as there is no discharge path for the same as already discussed in the previous section. Therefore such an arrangement of a diode in series with an ideal capacitor always detects the highest positive excursion of the input voltage if the latter is varying at random. If the diode polarity is reversed it detects the lowest voltage reached at the input. Such circuits are used in industrial setups to note the limits reached for any given duration. The capacitor must be discharged (reset) for the next period of operation.

SAQ 5

In the peak detector circuit of Figure 11.9, $v_s = 100 \sin 2\pi \times 50t$. Determine the output voltage across the capacitor.

SAQ 6

If in the Figure 11.8, the turns ratio of the transformer is 10:1, $C = 1000\ \mu$F, $R = 500\ \Omega$. Sketch the waveform across R under steady state conditions.

11.4.3 Clamper

In the same peak detector circuit of the previous section, if voltage is sensed across the diode then it will be $v_d = -V_p + V_p \sin wt$ because the capacitor gets charged to V_p in the direction shown in Figure 11.10(a). Therefore the output voltage v_d of the circuit is prevented from ever going positive or it is said to be clamped to zero as shown in Figure 11.10(b). The input voltage is in fact shifted downwards by an amount V_p to yield this output.

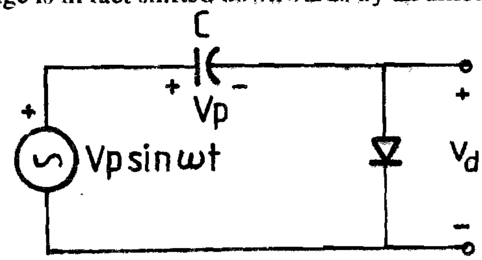


Figure 11.10 (a) : Clamping Circuit

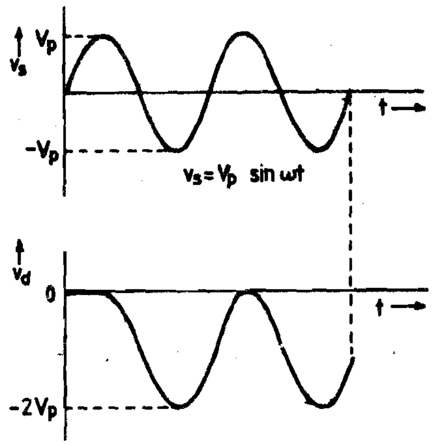


Figure 11.10 (b) : Waveforms of input and output voltages

SAQ 7

If in the clamping circuit of Figure 11.10(a), $V_P = 100$ V and $w = 500$ rad/s, sketch the voltage across the diode.

11.4.4 Voltage Multiplier

If the peak detector circuit is now connected to the clamping circuit as shown in Figure 11.11, it becomes a voltage doubler circuit. The voltage across the shunt diode exhibits a variation as in Figure 11.10 (a). The series diode and the output capacitor combine to detect the negative peak of this voltage viz. $2V_p$. The output capacitor therefore gets charged to $2V_p$.

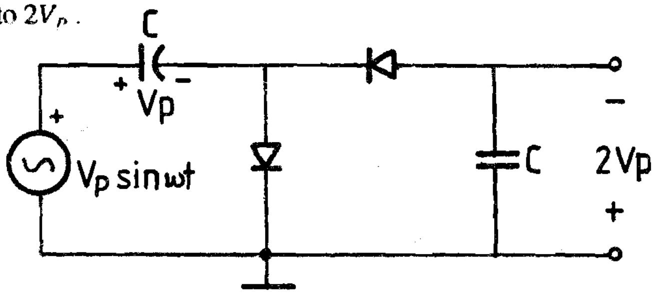


Figure 11.11 : Voltage Doubler

Figure 11.12 shows sections of such circuits cascaded to form a voltage multiplier circuit. Such voltage multiplier circuits can generate very high dc voltage if good quality capacitors are used. Such circuits are commonly used in ionizer equipment. The alternative of using a transformer to step up the a.c voltage followed by a simple ac-dc converter leads to a more expensive and bulky unit.

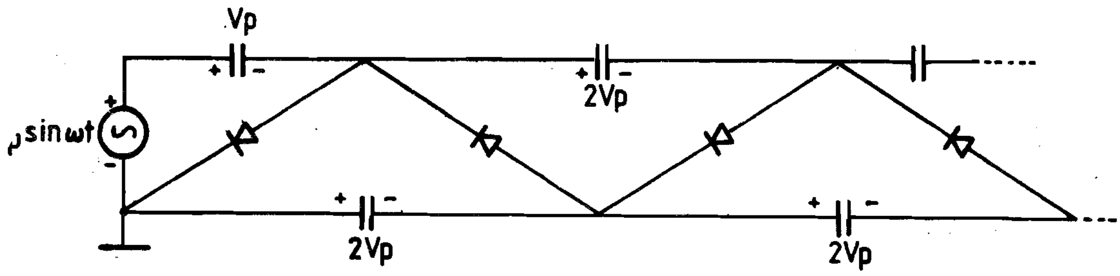


Figure 11.12 : Voltage Multiplier

SAQ 8

Obtain a voltage of 300 V dc from 100 sin *wt*, using diodes and capacitors.

Example 11.5

Clamp a symmetrical square wave of 10 V amplitude to 7 V. Its positive peak should be clamped to 7 V.

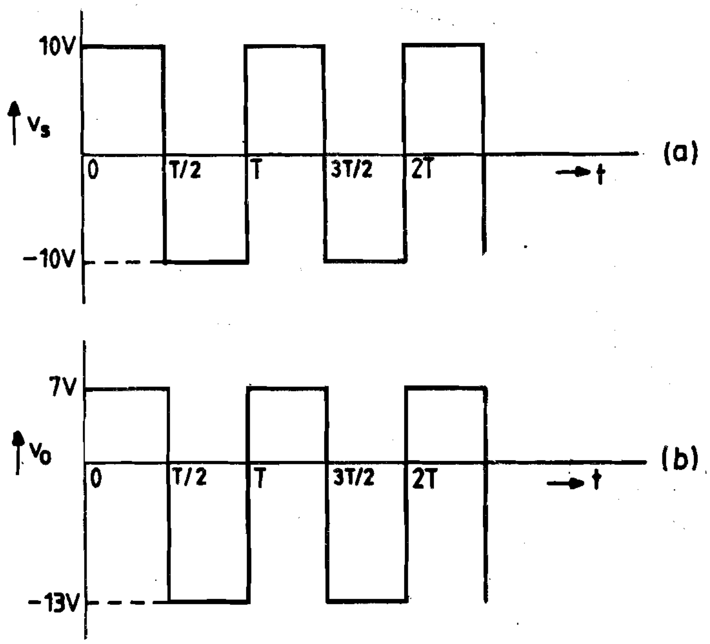


Figure 11.13 : For Example 11.5
(a) Input Voltage (b) Required output Voltage

Solution

See Figure 11.13 (c).

The capacitor gets charged to the peak value of voltage in the direction of the diode forward bias. It gets charged to 3 V. Therefore $v_o = v_S - 3$, yielding the required waveform.

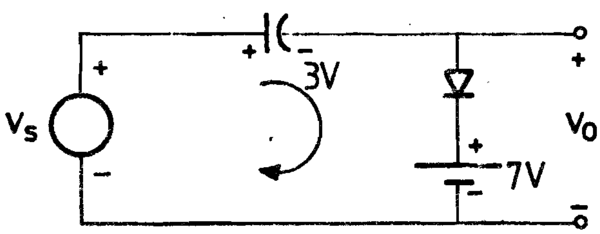


Figure 11.13 (c) : For solution to Example 11.5

SAQ 9

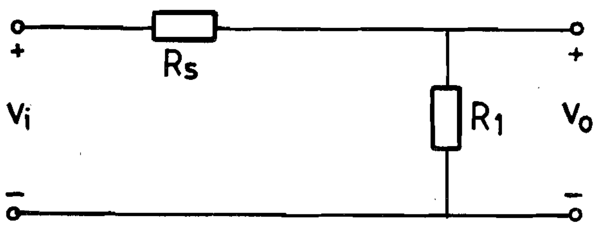
Clamp the square wave of 10 V amplitude shown in Figure 11.13(a) to – 7 V. Its maximum value should be clamped to – 7 V.

11.4.5 Diode Function Generator

Diodes and resistors with the help of voltage sources can be used to design circuits yielding certain types of nonlinear functional relationships between an output voltage V_0 and an input voltage V_i. $V_0 = f(V_i)$. Such a characteristic is called a transfer characteristic.

Examples of such circuits are given in Figure 11.14 (b) to (f). In the associated transfer characteristics the slopes of the straight line segments are marked alongside. The notation $R_x \,//\, R_y$ means the resistance value of the parallel combination of R_x and R_y i.e., $\frac{R_x R_y}{R_x + R_y}$.

Note that in each case, the transition from one slope to another occurs when the pertinent diode starts or stops conducting. Argue out the validity of each characteristic.



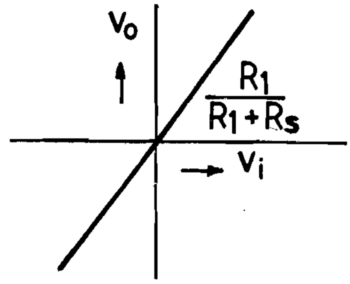
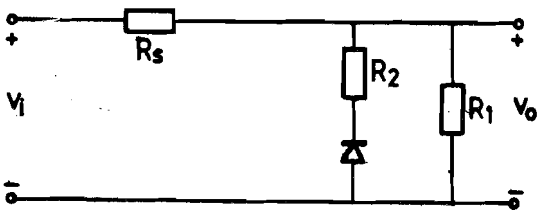


Figure 11.14 (a)



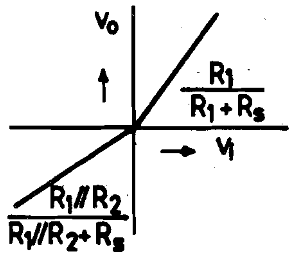
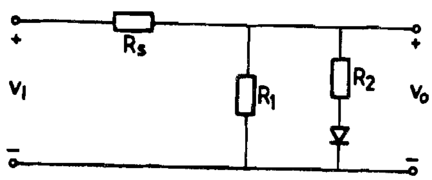


Figure 11.14 (b)



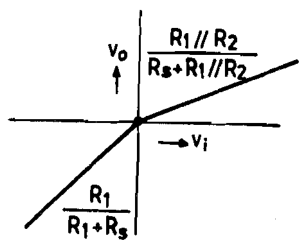
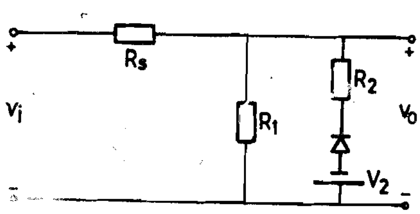


Figure 11.14 (c)



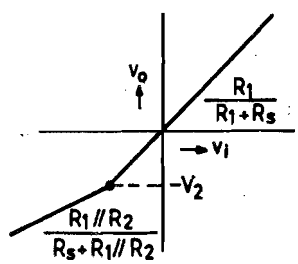


Figure 11.14 (d)

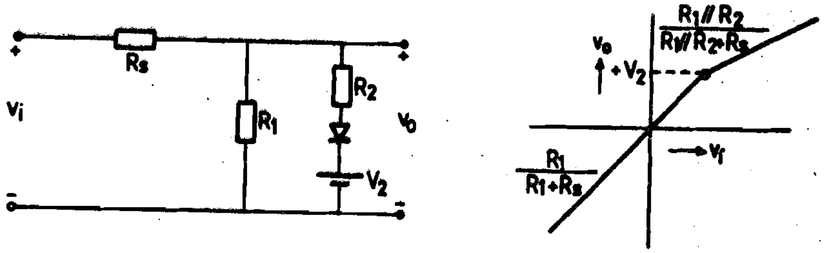
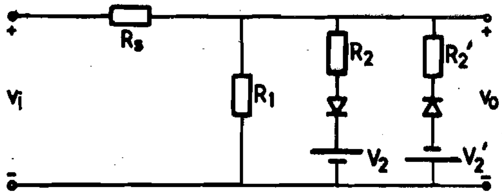


Figure 11.14 (e)



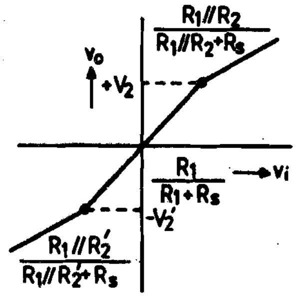


Figure 11.14 (f)

Figure 11.14 : Diode function generator circuits

Example 11.6

Design a diode function generator for a V_0 versus V_i characteristic as shown in Figure 11.15(a) (piecewise linear approximation). The slopes are marked alongside each segment within brackets.

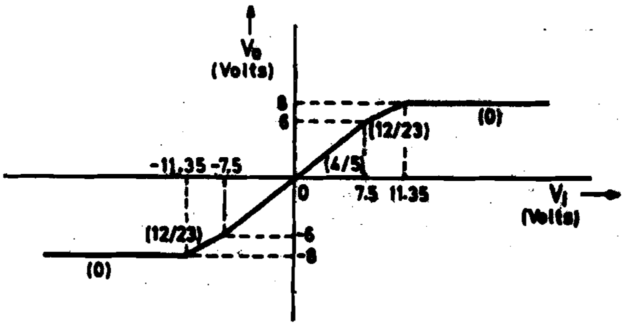


Figure 11.15 (a) : For Example 11.6

Solution

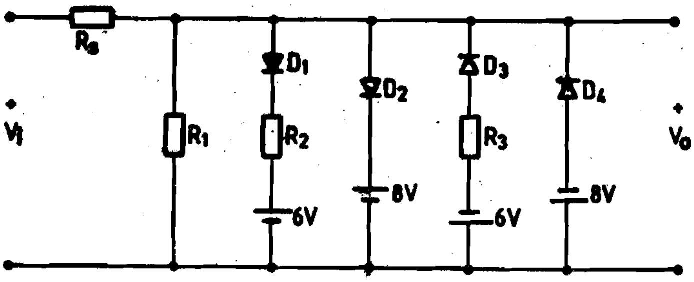


Figure 11.15 (b) : For solution to Example 11.6

The break points at ± 6V, ± 8V suggest a circuit as shown in Figure 11.15 (b) incorporating d.c sources of ± 6V and ± 8V

$-6 < V_o < 6$

For this range, none of the diodes conduct. Hence,

$$\frac{V_o}{V_i} = \frac{R_1}{R_1 + R_s} = \frac{4}{5}, \text{ yielding } R_1 = 4R_s$$

$6 < V_o < 8$

Diode D_1 alone conducts, all other diodes are blocked.

From Figure 11.14 (e),

$$\text{Slope of characteristic} = \frac{\Delta V_o}{\Delta V_i} = \frac{R_1 // R_2}{R_1 // R_2 + R_s} = \frac{12}{23}$$

$$\text{Hence, } \frac{R_2\,(4R_s)}{R_2 + 4R_s} = \frac{12}{23}\left[R_s + \frac{R_2\,(4R_s)}{R_2 + 4R_s}\right],$$

which yields $R_2 = 1.5\,R_s$

$V_0 = 8$

Diode D_2 conducts clamping V_0 at 8 V.

By symmetry,
$R_3 = R_2 = 1.5\,R_s$. Let $R_s = 2R$. Then, $R_2 = R_3 = 3R$; $R_1 = 8R$.
Any suitable value of R, say 1 kΩ, may be chosen.

Example 11.7

If a triangular waveform of peak value 10 V is applied to the function generator circuit of Example 11.6 as v_i, sketch v_0.

Solution

When $v_0 = 6$, $\frac{v_0}{8R} \times 2R = \frac{v_0}{4}$ is the voltage drop across 2 R.

Therefore, $v_s = 1.25\,v_0 = 1.25 \times 6 = 7.5$ V

When $v_0 = 8$ V, drop across 2 $R = \frac{8 \times 2R}{8R} + \frac{2 \times 2R}{3R} = 3.33$ V

Therefore $V_i = 8 + 3.33 = 11.33$ V

when $v_i = 10$ V, it is clear from the above that $v_0 < 8$ V. We then have from the node equation at the output terminal,

$$v_0\left[\frac{1}{2R} + \frac{1}{3R} + \frac{1}{8R}\right] - \frac{10}{2R} - \frac{6}{3R} = 0, \text{ yielding } v_0 = 7.3 \text{ V}.$$

By symmetry, the values of v_0 for negative v_i can be deduced. The above analysis is made starting from the circuit of Figure 11.15 (b). Alternatively, the correspondence between v_0 and v_i can be directly deduced from the transfer characteristic of Figure 11.15 (a). The triangular input voltage v_i and the output voltage v_0 are plotted in Figure 11.16.

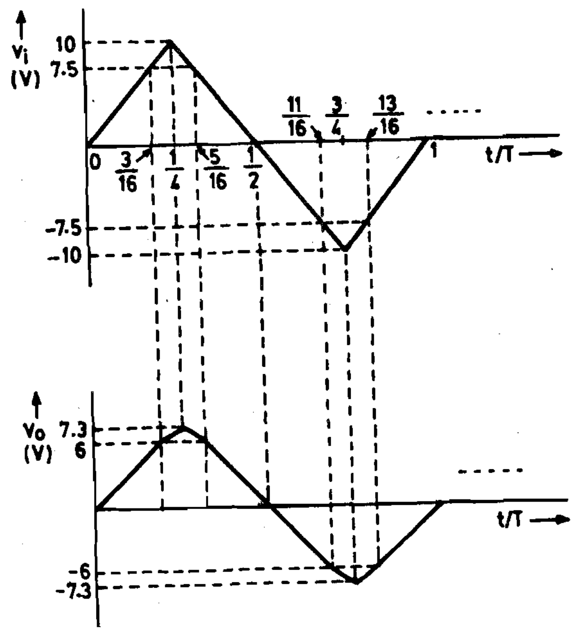


Figure 11.16 : Waveforms in Example 11.7

Diode function generators are commonly employed in circuits to convert triangular waveform into a sinusoidal waveform. The circuit used may be similar to that of Figure 11.15 (b) but with a greater number of parallel branches.

SAQ 10

In the diode function generator circuit of 11.14(f). $R_s = 1\ k\Omega$, $R_1 = 2\ k\Omega$, $R_2 = 2\ k\Omega$ and $V_2 = V_2' = 1$ V. Sketch V_0 versus V_i.

11.4.6 Regulated Power Supply

You may observe from Figure 11.3 that the Zener diode mantains its reverse bias voltage nearly constant at a value V_z, when the reverse current exceeds a certain minimum value I_{knee} corresponding to the bend (or knee) of the curve in the breakdown region. In this region any change in the current is accompanied by only a very small change in voltage. In other words, the incremental Zener resistance $r_z = \frac{\Delta V}{\Delta I}$ in this region is very very small.

This property is made use of in many regulated d.c power supply units, which are intended to furnish a nearly constant d.c output voltage irrespective of the fluctuations in the primary supply and the load current. The circuit of Figure 11.17 illustrates one such arrangement.

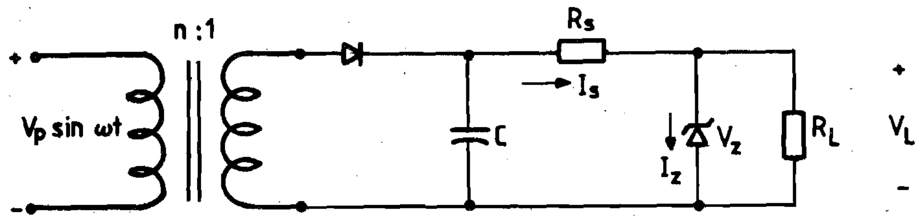


Figure 11.17 : Circuit of a Regulated (zener) dc Power supply fed from Power Line Voltage

It is clear from the circuit that

$$I_S = \frac{\frac{V_P}{n} - V_z}{R_S}; \quad I_z = \frac{\frac{V_P}{n} - V_z}{R_S} - \frac{V_L}{R_L} \text{ and } V_L = V_z.$$

Let us assume that $I_{knee} < I_z < I_{zmax}$, where I_{zmax} is the maximum permitted reverse current in the Zener diode (a value which is usually specified by the manufacturer).

Now following tthe analysis of Section 11.4.1, we note that capacitor loses a charge equal o $I_S T$ between successive charging periods. Hence Δv_C the peak to peak ripple voltage across the capacitor is

$$\Delta v_C = \frac{I_S T}{C} = \frac{\left(\frac{V_P}{n} - V_z\right) T}{R_S C}$$

The corresponding change in the output voltage V_L is however given by

$$\Delta V_L = \Delta v_C \cdot \frac{r_z // R_L}{R_S + r_z // R_L}$$

Therefore,

$$\left(\frac{V_P}{n} - V_z\right) \frac{T}{R_S C} \times \frac{r_z // R_L}{r_z // R_L + R_z}$$

is the ripple voltage at the output, where r_z is the Zener small signal resistance at its operating point I_z.

Example 11.8

Let in the circuit of Figure 11.17,

$V_p = 220\sqrt{2}$ V ; $n = 10$; $w = 100\pi$ rad/s ;

$V_z = 15$ V ; $C = 1000\ \mu$F ; $R_L = 100\Omega$; $R_S = 100\Omega$; $r_z = 5\ \Omega$

Now $V_L = 15$ V ; $\frac{V_P}{n} = 31.1$ V

$$I_z = \frac{-15}{0.1} + \frac{31.1 - 15}{0.1} = 11 \text{ mA}$$

$I_S = 161$ mA

$I_L = 150$ mA

$$\text{Peak to peak ripple voltage across the capacitor} = \frac{161 \times 10^{-3} \times 2 \times 10^{-2}}{1000 \times 10^{-6}} = 3.22 \text{ V}$$

$$\text{Peak to peak ripple voltage at the output} = 3.22 \times \frac{(5//100)}{100 + (5//100)}$$

$$= \frac{3.22 \times 1}{1 + 20 + 1} = \frac{3.22}{22} = 0.146 \text{ V}$$

Thus the output voltage is closely regulated.

SAQ 11

In the circuit of a regulated (Zener) dc power supply shown in Figure 11.17 $V_p = 220$ V, $w = 2\pi \times 50$, $n = 10$, $C = 1000\ \mu$F, $R_S = 500\Omega$, $V_z = 20$ V and $R_L = 1$ kΩ. Determine the dc output voltage and peak to peak ripple across the capacitor.

11.4.7 Analog Diode Gate

Consider the circuit of Figure 11.18 (a), where the switch S is used connect a load R_L to a source or disconnect from it.

(a) When the switch S is closed, the signal source gets connected to the load. R_S is the source resistance. Therefore

$$V_0 = V_S \frac{R_L}{R_L + R_S}$$

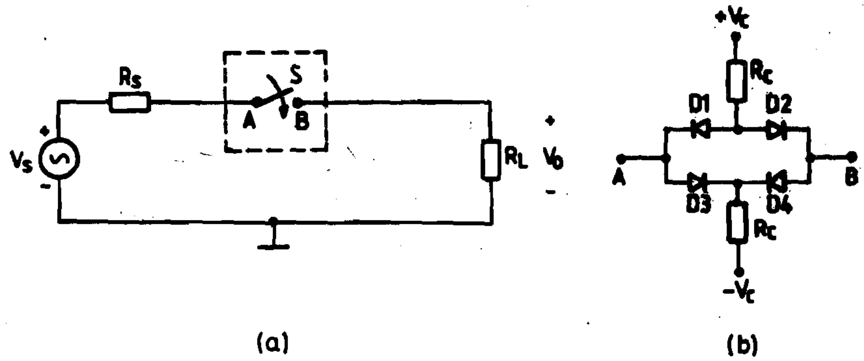


Figure 11.18 : Illustrating the action of an Analog diode gate

(a) A circuit containing a switch S (b) Diode circuit replacing S

(b) When Switch S is opened, the source gets disconnected from the load and $V_0 = 0$.

Instead of operating mechanically, such a switch can be voltage controlled if the arrangement of diode bridge shown in Figure 11.18 (b) replaces the dotted portion of Figure 11.18 (a). The operation of the resulting electronic switch is explained below.

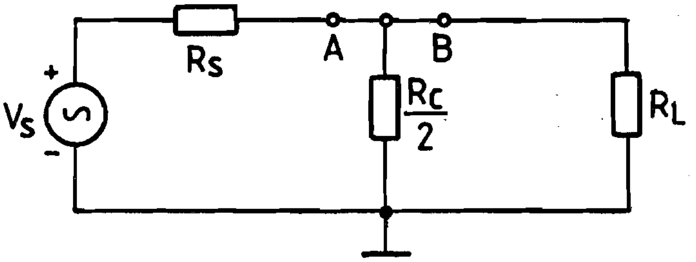


Figure 11.19 (a) : Equivalent circuit when diode switch is closed

(a) When V_C is positive, diodes D_1, D_2, D_3 and D_4 can get forward biased and hence they act as short circuits. Consequently the equivalent circuit of Figure 11.18 (a) incorporating the diode bridge becomes one as shown in Figure 11.19 (a). The resistor $R_C/2$ represents the combined effect of the two resistors R_C in Figure 11.18 (b).

(b) When V_C is negative, diodes D_1, D_2, D_3 and D_4 can get reverse biased and hence they act as open circuits. Consequently the equivalent circuit is as shown in Figure 11.19 (b). As long as $|V_C| > |V_S|$, the diodes remain reverse biased and $V_0 = 0$. It simulates the situation when switch S is open in Figure 11.18 (a).

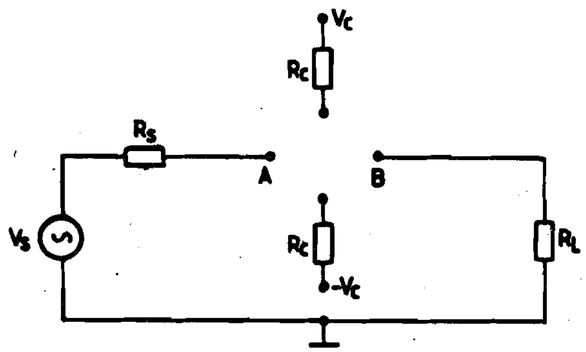


Figure 11.19 (b) : Equivalent Circuit when diode switch is open

Therefore the source can be connected to the load or disconnected from the load depending upon the polarity of voltage selected for V_C with certain conditions regarding its magnitude being satisfied.

Example 11.9

Let a square wave v_c be applied in place of a dc voltage V_C in the circuit discussed above. If its magnitude is 60 volts and its frequency is 500 Hz, sketch the output waveform v_0 when v_s is a symmetric triangular waveform with time period 8 m sec and peak voltage of 60 V.

$$R_s = R_L = R_C = 15 \text{ k}\Omega .$$

Solution

When the diode switch is closed (vide Figure 11.19 (a)), R_L comes in parallel with $R_C/2 = 7.5$ kΩ, providing an effective resistance of 5 kΩ.

Hence, $$v_0 = \frac{5}{5+15} v_s = \frac{v_s}{4}$$

The diode switch is closed for those time intervals when $v_C > 0$ and $v_C > |v_s|$. During these intervals $v_0 = v_s/4$, as already seen. v_0 is zero for other time intervals. The waveforms of v_c, v_s and output v_0 are given in Figure 11.20.

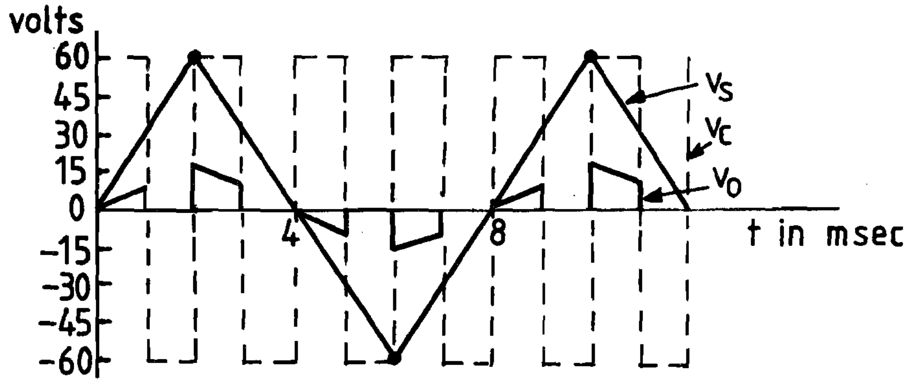


Figure 11.20 : For solution to Example 11.9

SAQ 12

In the analog diode gate shown in Figure 11.18, $R_s = 10\ k\Omega$, $R_L = 20\ k\Omega$, $R_C = 10\ k\Omega$. Sketch the output waveform for the same input waveform and control signal shown in Example 11.9.

11.4.8 Digital Gates

We now include a brief account of the use of diodes in the design of two types of digital gates. You will learn more fully the details of digital gates and their uses in Unit 16. You may like to review this Secion after completing the study of Unit 16. Digital systems operate on the basis of two states, the presence or absence of a voltage represented by two (binary) numbers 1 and 0 respecively, as shown in the following table.

Digital Signal	*Voltage level*
logic '0'	0 V
logic '1'	5 V (say)

'OR' Gate

Consider the circuit of Figure 11.21, where the two input voltages A and B can be either high (5 V) or low (0 V) corresponding to logic 1 or 0. Now when either A or B or both are at 5 V, C is also at 5 V as one or the other or both diodes conduct. C is a 0 V only when neither diode conducts i.e., when both A and B are at 0 V. The various combinations of inputs and the corresponding output in terms of voltages and in terms of logic levels 1 and 0 are given in the tables below. The latter table in terms of binary numbers is called the *truth table*. The above circuit constitutes what is called an 'OR' Gate and C is expressed in terms of A and B symbolically by

$C = A + B$.

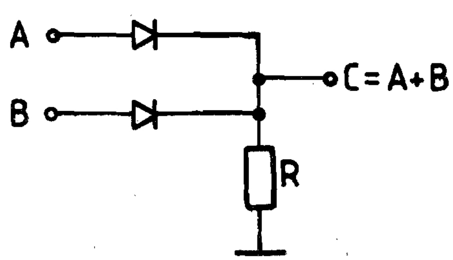


Figure 11.21 : Logic gate 1 : 'OR' gate

nputs in V		Output in V
A	*B*	*C*
0	0	0
5	0	5
0	5	5
5	5	5

Truth Table of 'OR' gate

A	*B*	C
0	0	0
1	0	1
0	1	1
1	1	1

Logic Operation $C = A + B$

The number of inputs need not be limited to 2 in an 'OR' gate (See Example 11.10)

'AND' Gate

The second gate we would study is the 'AND' gate, where the output C is high only if both A and B are high and zero otherwise. The circuit realisation of this gate is given in Figure 11.22 and the input-output combinations in the tables below :

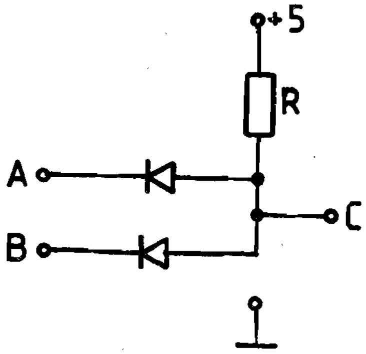


Figure 11.22 : Logic gate 2 : 'AND' gate

Inputs in V		Output in V
A	*B*	*C*
0	0	0
0	5	0
5	0	0
5	5	5

Truth Table of 'AND' gate

A	*B*	C
0	0	0
0	1	0
1	0	0
1	1	1

Logic Operation $C = A.B$

The number of inputs need not be limited to two in an 'AND' gate (See Example 11.11)

Example 11.10

Draw a four input 'OR' gate circuit.

Solution

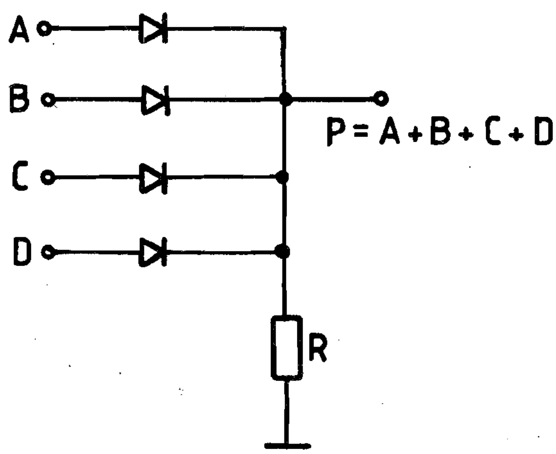


Figure 11.23 : For solution to Example 11.10

Example 11.11

Draw a four input 'AND' gate circuit.

Solution

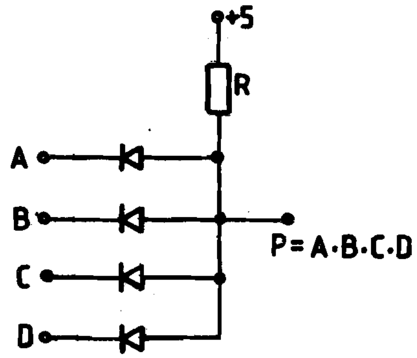


Figure 11.24 : For solution to Example 11.11

SAQ 13

Draw the circuits for a 3 input 'OR' gate and a 3 input 'AND' gate.

11.5 SUMMARY

The unit started with a discussion on conduction mechanism in solids. Conduction mechanism in semiconductors is highlighted. Intrinsic semiconductor, *n*-type and *p*-type semiconductors are discussed. The *pn* junction, its characteristics and applications are brought out in detail.

11.6 ANSWERS TO SAQs

SAQ 1

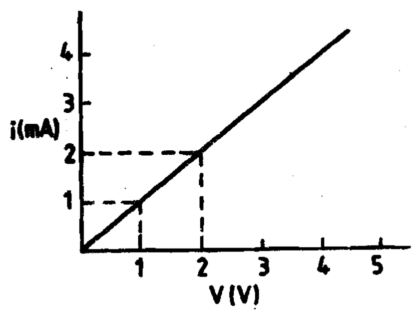


Figure for Answer to SAQ 1

SAQ 2

Assuming $i = 5$ mA,

$$v \approx 26 \times 10^{-3} \ln \left(\frac{5 \times 10^{-3}}{100 \times 10^{-9}} \right) \text{volts}$$

$= 0.281$ V

Using this value of v,

$i = (5 - 0.281)\,10^{-3}$ A $= 4.719$ mA.

Then v would be

$v = 26 \times 10^{-3} \ln(4.719 \times 10^4) = 0.280$ V

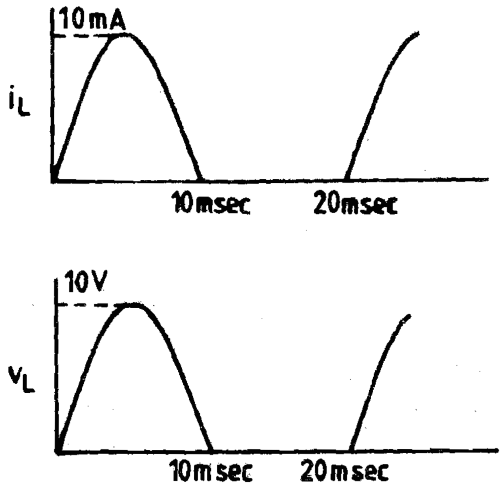
Using this revised value of v,

$i = (5 - 0.280) \times 10^{-3}$ A $= 4.720$ mA

This is close enough to the earlier value.

Thus $i = 4.72$ mA; $v = 280$ mV.

SAQ 3



Figures for Answer to SAQ 3

SAQ 4

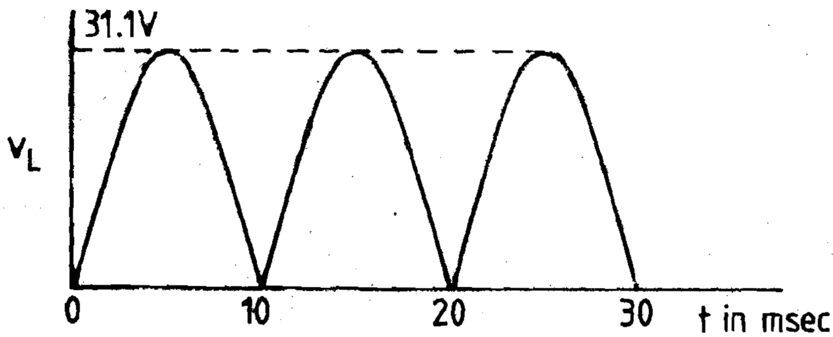


Figure for Answer to SAQ 4

SAQ 5

100 V d.c.

SAQ 6

$T/RC = 20 \times 10^{-3} / 500 \times 1000 \times 10^{-6} = 0.04 << 1.$

Peak-to-peak voltage dip $= \dfrac{V_P}{n} \times \dfrac{T}{RC} = \dfrac{220\sqrt{2}}{10} \times 0.04 = 1.244$ V.

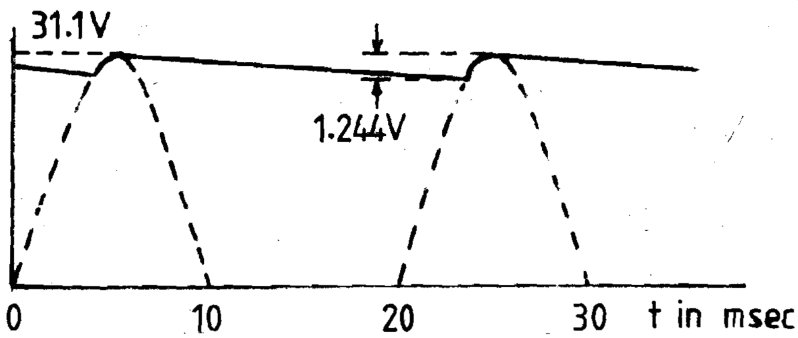


Figure for Answer to SAQ 6

SAQ 7

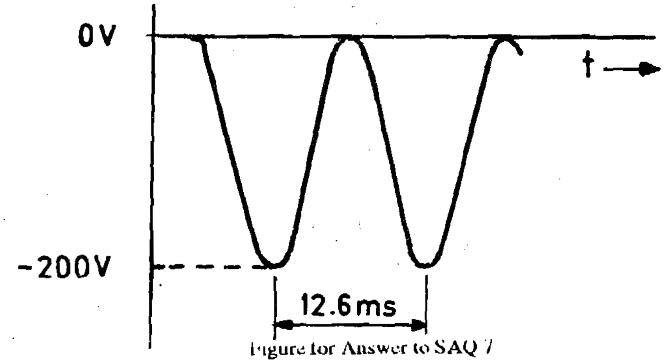


Figure for Answer to SAQ 7

SAQ 8

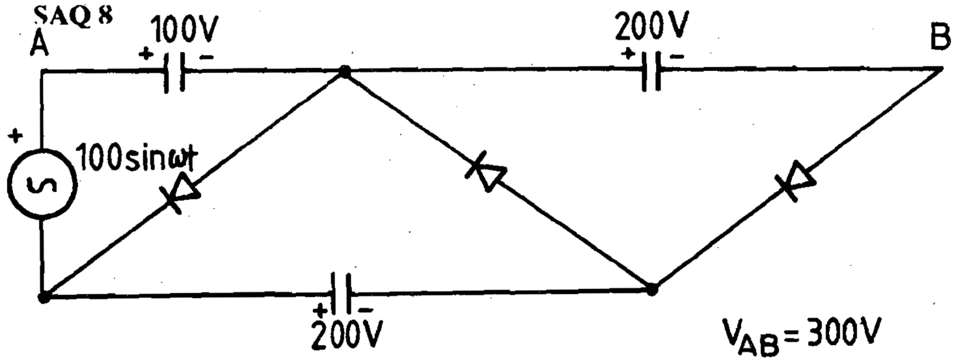


Figure for Answer to SAQ 8

SAQ 9

In the circuit shown, v_c gets clamped to + 17V.

Therefore the output voltage v_0 is $v_s - v_c = v_s - 17$, which has the required waveform.

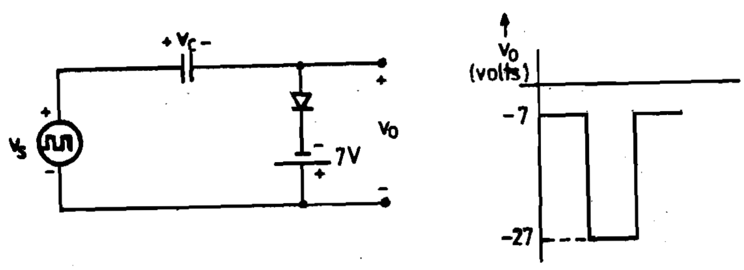


Figure for Answer to SAQ 9

SAQ 10

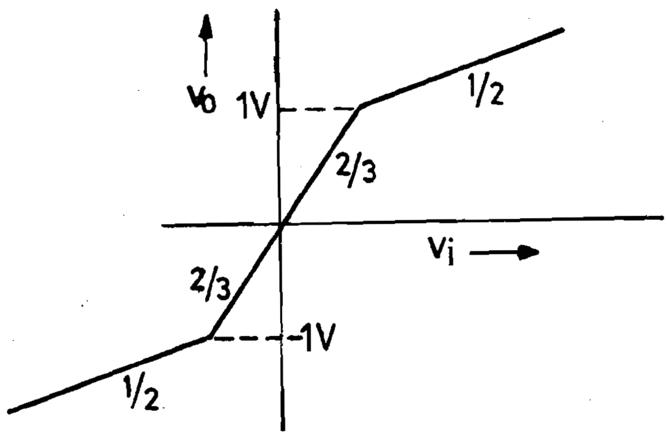


Figure for Answer to SAQ 10

SAQ 11

DC output = 20 V

$$\text{Ripple across the capacitor} = \frac{(31.1 - 20) \times 0.02}{1000 \times 10^{-6} \times 500}$$

$$= 0.444 \text{ volts}$$

SAQ 12.

Figure (a) shows the equivalent circuit when the switch is closed.

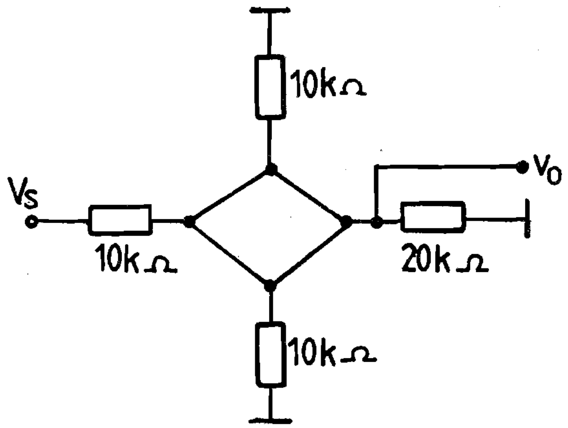


Figure (a) for Answer to SAQ 12

When the switch is closed $v_O = \frac{20 /\!/ 5}{10 + (20 /\!/ 5)} v_s = \frac{2}{7} v_s$.

$v_O = 0$, when the switch is open.

The output waveform is shown in Figure (b).

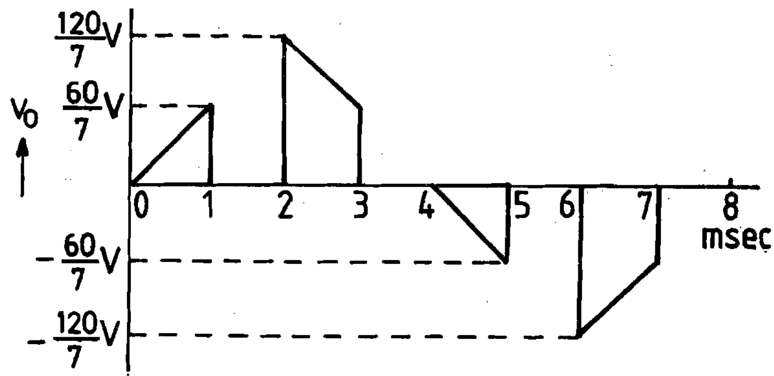
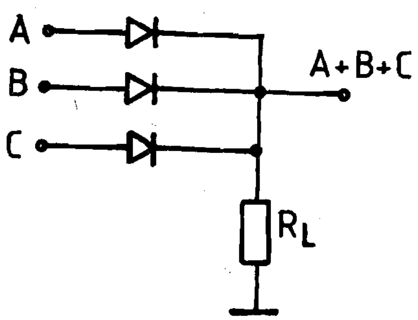
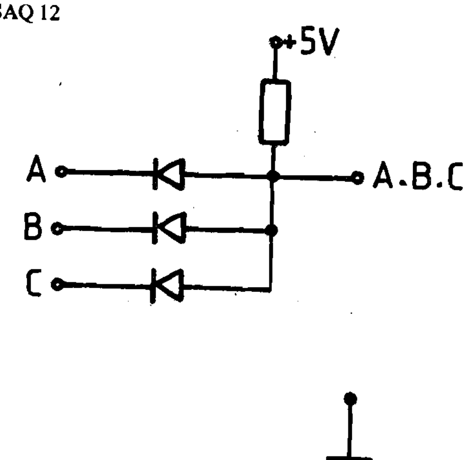


Figure (b) for Answer to SAQ 12

SAQ 13



(a) 3 - input 'OR' gate



(b) 3 - input 'AND' gate

Figure for Answer to SAQ 13