Special Diodes

4

4.1 Introduction

The most common diodes are rectifier diodes. These *PN*-junction diodes act as an electronic check valve and are used to convert ac voltage to dc voltage. There are several other diodes that can be used for many specific applications. These special types of diodes' characteristics can be tailored by proper selection of semiconducting materials, doping and biasing. This chapter covers Zener diode, varacter diode, tunnel diode, photodiode, LED, Schottky, Gunn and IMPATT diode.

Zener diodes operate in reverse breakdown region. At breakdown, these diodes maintains constant voltage. Therefore, these are used as voltage regulator, voltage reference, wave shaper etc. Varacter diode is reverse biased *PN*-junction diode. Its characteristic shows the variation of junction capacitance with reverse bias. It find application in low noise microwave devices, ... electronic tuning etc. Tunnel diode is made of GaAs/Ge semiconductor. It is a ... high speed switching devices.

4.2 Zener Diode

Normal *PN*-junction diode can easily operate in forward bias and also in reverse bias. If the reverse voltage exceeds the breakdown voltage, large current flows through the junction, which may destroy the diode. The Zener diode can be designed to operate in the breakdown region. The voltage across Zener diode is almost constant over most of the breakdown region. The Zener diode normally remains safe as long as current does not exceed the maximum permissible value I_{ZM} as provided by the manufacturer. If current is greater than I_{ZM}, the diode may be destroyed.

Figure 4.1 shows the typical Zener diode characteristic with its circuit symbol. It is found that *V-I* curve is similar to that of normal diode in the forward region. A very small current flows in the leakage region. As reverse voltage reaches the breakdown voltage V_Z, breakdown occurs : results in almost vertical increase in the current.

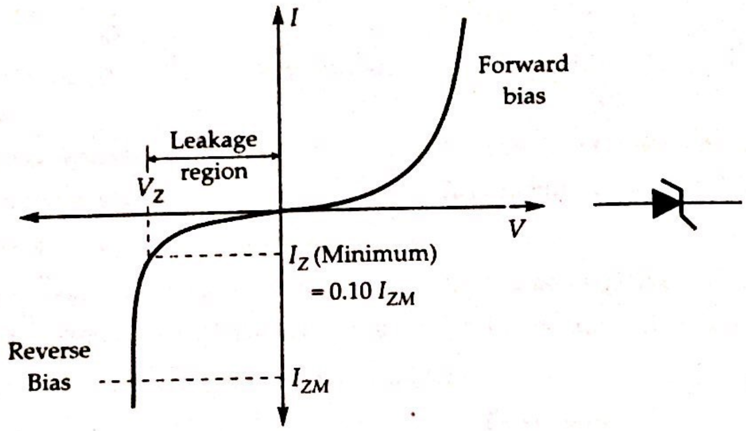


Figure 4.1 *V-I* characteristics of a Zener diode and circuit symbol

The maximum Zener current I_{ZM}, which the Zener can withstand depends on construction and design of the diode. These diodes are high power devices. The power dissipation through a Zener diode can be calculated by

$$P_Z = V_Z I_Z \quad \text{...(4.1)}$$

Data sheet usually provides maximum Zener current I_{ZM}, which can flow through it without damaging the Zener diode.

$$I_{ZM} = \frac{P_{ZM}}{V_Z} \quad \text{...(4.2)}$$

where I_{ZM} = Maximum rated Zener current,

P_{ZM} = Power rating or Power at which the Zener diode can withstand, and

V_Z = Zener voltage

Commercially available Zener diodes have power rating between 0.25 W to more than 50 W. For example, a 2 W and 20 V Zener can operate safely at current upto 100 mA.

There are *two* mechanisms for large reverse current in breakdown region (*i*) *Avalanche breakdown* and (*ii*) *Zener breakdown*.

When doping is small, breakdown voltage is large (>6 V), then avalanche effect is responsible for breakdown. In this case thermally generated minority carriers get accelerated to high enough speed to break the covalent bond by collision. A new electron-hole pair is generated. This pair acquires sufficient energy from the external applied field to collide with another covalent bond and further generates new electron-hole pair. This process continues to disrupt the ions that results in a large reverse current.

Second mechanism is predominant when a diode is heavily doped, the depletion layer becomes very narrow. Due to this, very strong electric field (applied voltage divided by depletion width) across the depletion layer arises. Approximately 10^7 V/m field produces across junction that causes direct rapture of covalent bond. As a result, large number of electron-hole pairs are generated, which contribute to large Zener current. This effect or mechanism is known as *Zener effect*. Here breakdown voltage is less than 6 V. Generally all diodes used in the breakdown region are known as *Zener diodes*. This is due to earlier discovery of Zener effect than the *avalanche effect*.

4.3 Zener Diode as Voltage Regulator

Zener diode under reverse bias (breakdown $V > V_Z$) maintains a constant voltage across itself even if current through it changes, as shown in Fig. 4.1. This property can be exploited to design a voltage regulator circuit for maintaining the output voltage of a power supply constant. When Zener diode is used in a circuit, we must ensure that the Zener current I_Z is limited by the external resistance so that the power dissipation $V_Z I_Z$ in the Zener is within the maximum rating specified by the manufacturer.

Figure 4.2 shows the circuit of a voltage regulator. The Zener diode is reverse biased ($V > V_Z$), so that it can operate in the breakdown region and maintain the load voltage constant (equal to Zener voltage). Any variations of input voltage or load resistance cannot disturb the load voltage.

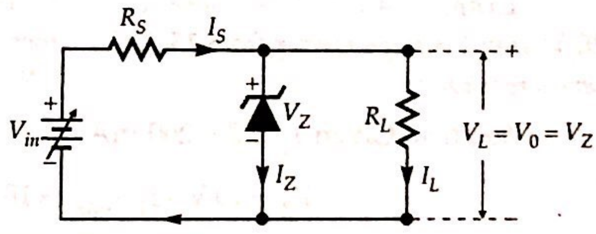


Figure 4.2 A Zener voltage regulator circuit.

A resistor R_S is necessary to limit the reverse current through Zener diode to safer value. R_S is selected for a given input voltage such that the diode operates in the breakdown region. R_S absorbs the voltage fluctuations so as to maintain load voltage constant.

In Fig. 4.2, the current through the series resistance R_S is given by :

$$I_S = \frac{V_{in} - V_Z}{R_S} \quad ...(4.3)$$

For total current I_S, apply KCL as follows :

$$I_S = I_Z + I_L \quad ...(4.4)$$

Load current I_L can be obtained from Ohm's law :

$$I_L = \frac{V_L}{R_L} = \frac{V_Z}{R_L} \quad ...(4.5)$$

($V_L = V_Z$; as load resistor and Zener diode are parallel)

In this discussion it is assumed that the Zener diodes operates in the breakdown region. When input voltage increases, I_S increases, at the same time Zener current, I_Z increases (because of low resistance) without much change in the Zener voltage. Hence the load voltage ($V_L = V_Z$) remains constant. On the other hand, let R_L decreases by keeping input voltage (V_{in}) constant. Load current I_L increases. Since total current I_S remains constant, therefore Zener current I_Z will decrease. Any small change in the Zener current I_Z do not affect the Zener voltage. So the output voltage V_L remains constant. Further, to assure that Zener diode operates in the constant voltage (break down) region, the extreme conditions of input and output are :

(i) Zener current I_Z is maximum *i.e.,* $(I_Z)_{max}$, when load current I_L is minimum *i.e.,* $(I_L)_{min}$ and input voltage (V_{in}) is maximum *i.e.,* $(V_{in})_{max}$.

(ii) Zener current I_Z is minimum *i.e.,* $(I_Z)_{min}$ when load current I_L is maximum *i.e.,* $(I_L)_{max}$ and input voltage (V_{in}) is minimum *i.e.,* $(V_{in})_{min}$.

(iii) For breakdown operation, $V_{TH} > V_Z$ where V_{TH} is the voltage that exists when the Zener diode is disconnected from the circuit.

It can be obtained as :

$$\text{Thevenin voltage, } V_{TH} = \frac{R_L}{R_S + R_L} \cdot V_{in} \qquad \text{...(4.6)}$$

***Example. 4.2** A Zener diode has specifications $V_Z = 5.2$ V and $(P_Z)_M = 260$ mW. Assume $R_Z = 0$. Find the maximum allowed current I_Z when Zener diode acts as a regulator.*

Solution. Given : $P_{ZM} = 260$ mW, $V_Z = 5.2$ V, $R_Z = 0$

From Ohm's law ;

$$(I_Z)_{max} = I_{ZM} = \frac{P_{ZM}}{V_Z} = \frac{260 \times 10^{-3}}{5.2} = 50 \text{ mA}$$

***Example 4.3** For the circuit shown in Fig. 4.4, find the maximum and minimum values of Zener current.*

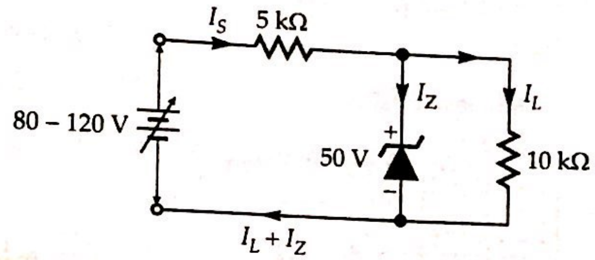


Figure 4.4

Solution. (*i*) For minimum current, input voltage should be minimum.

$\therefore \quad V_{in} = 80$ V, $V_Z = 50$ V

From KVL, $\quad (V_{in})_{min} = V_S + V_Z$

$$V_S = (V_{in})_{min} - V_Z = 80 - 50 = 30 \text{ V}$$

From Ohm's law, $\quad I_S = \dfrac{V_S}{R_S} = \dfrac{30}{5 \times 10^3} = 6 \text{ mA}$

In this case, $\quad$ load current $(I_L) = \dfrac{V_L (= V_Z)}{R_L} = \dfrac{50}{10} = 5 \text{ mA}$

From KCL, $\quad I_S = I_Z + I_L \quad \therefore \quad I_Z = I_S - I_L$

Minimum Zener current $(I_Z) = 6 - 5 = 1$ mA

(*ii*) For maximum Zener current input voltage should be maximum.

$\therefore \quad V_{in} = 120$ V, $\quad V_Z = 50$ V

From KVL, $\quad (V_{in})_{max.} = V_S + V_Z \quad \Rightarrow \quad V_S = 120 - 50 = 70$ V

From Ohm's law, $\quad I_S = \dfrac{V_S}{R_S} = \dfrac{70}{5 \times 10^3} = 14 \text{ mA}$

Since, $I_L = 5$ mA (calculated)

Therefore on applying KCL, $\quad I_Z = I_S - I_L$

Maximum Zener current $(I_Z) = 14 - 5 = 9$ mA

4.4 Varactor Diode

It is a two terminal *PN*-junction diode with small doping. At the *PN*-junction, depletion layer is formed, which acts like a dielectric in a capacitor (with *P* and *N* regions are behaving like plates of a capacitor) having capacitance of the order of some pico-Farad (pF), known as junction, barrier or *transition capacitance*. When diode is reverse biased, depletion width increases with the reverse voltage, and its capacitance becomes smaller. In general, since the thickness of depletion region varies with the applied bias voltage, capacitance of the diode can be made to vary. It is konwn as *varactor* (*variable + reactor*), *varicap*, *tunning diode* etc. Usually capacitance is inversely proportional to the width of depletion region and width of depletion region is proportional to the square root of the applied voltage.

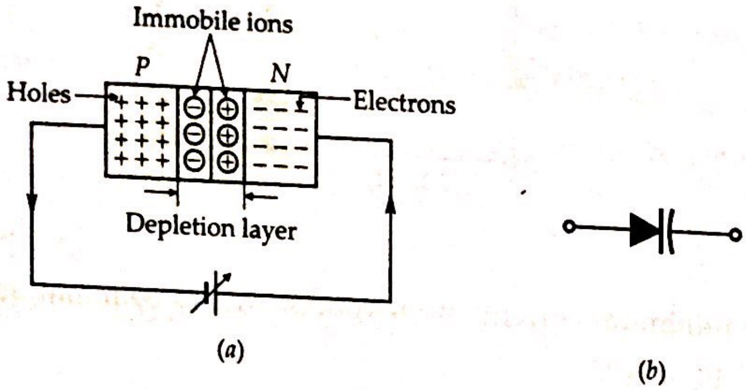


Figure. 4.5 (*a*) Reverse biased *PN*-junction with depletion layer. (*b*) Circuit symbol.

Therefore, capacitance is inversely proportional to the square root of the external applied voltage as shown in Fig. 4.6.

$$C_T(V) = \frac{K}{(V_T + V_R)^n} = \frac{C_T(0)}{\left(1 + \frac{V_R}{V_K}\right)^n} \qquad ...(4.7)$$

where K is constant, which depends on semiconductor ; V_T is volt equivalent temperature and V_R is the reverse voltage applied ; $n = \frac{1}{2}$ for alloyed junction and $\frac{1}{3}$ for diffused junction. $C_T(0)$ is capacitance at zero voltage ; V_K is barrier potential.

Figure 4.6 shows the variation of capacitance with reverse voltage. At zero volt, depletion region is small and hence capacitance is large (≈600 pF). Capacitance decreases with increasing reverse voltage and it becomes approximately 30 pF at reverse voltage of 15 V.

The varactor diodes are used in FM receiver, TV receiver and in tunning of LC parallel resonant circuit in microwave frequency multiplier, parametric amplifier, bandpass filters.

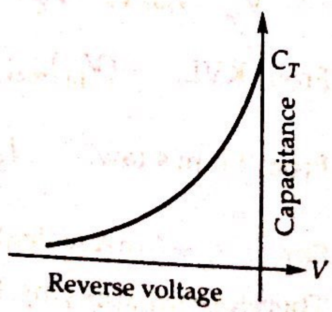


Figure 4.6 Capacitance C_T vs. reverse voltage.

Example 4.4 *A varactor diode with a linearity graded doping has a capacitance of 100 μF when no bias is applied to the diode. Determine the junction capacitance for the silicon (Si) diode when reverse bias of 8 V is applied to the diode.*

Solution. Given : $C_T(0) = 100\,\text{pF}$, $V_K = 0.7\,\text{V}$, $V_R = 8\,\text{V}$ and $n = \frac{1}{3}$

We know that, $$C_T(V) = \frac{C_T(0)}{\left(1 + \frac{V_R}{V_K}\right)^n} = \frac{100}{\left(1 + \frac{8}{0.7}\right)^{1/3}} = 43.18\,\text{pF}$$

Example 4.5 *A varactor diode has a capacitance of 15 pF at 5 V reverse bias voltage. Determine the capacitance if the diode bias voltage is increased to 20 V.*

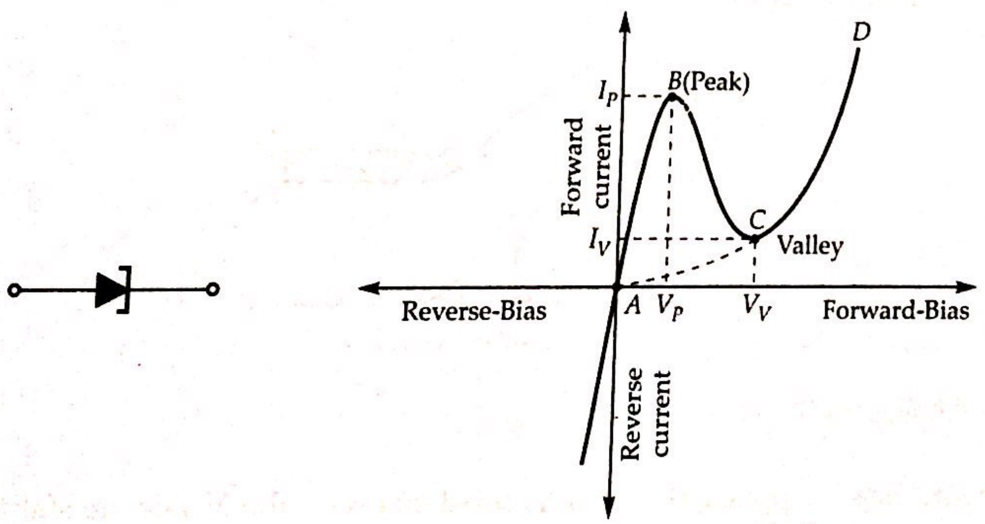
Solution. Given $C_1 = 15\,\mu\text{F}$, $V_1 = 5\,\text{V}$ and $V_2 = 20\,\text{V}$.

Consider varactor diode has alloyed junction *i.e.*, $n = \frac{1}{2}$

Thus, $C \propto \frac{1}{V^{1/2}}$ $\quad \therefore \quad \frac{C_1}{C_2} = \sqrt{\frac{V_2}{V_1}}$ $\quad$ or $\quad C_2 = \sqrt{\frac{V_1}{V_2}}.C_1 = \sqrt{\frac{5}{20}} \times 15 = 7.5\,\text{pF}$

4.5 Tunnel Diode

Tunnel diode was discovered by L.Esaki in 1958. So it is also known as *Esaki diode*. It is a *PN*-junction diode with extremely high doping (1 part in 10^3) on each side of the junction. Since impurity is increased beyond that in Zener diode, the depletion layer becomes very thin ($\approx 10^{-8}$ m) and reverse breakdown voltage approaching to zero. The circuit symbol of tunnel diode is shown in Fig. 4.7(*a*). The *PN*-junction diode with nearly zero breakdown voltage is known as tunnel diode because of very thin depletion layer, electrons can tunnel across the junction in the forward bias voltage. With increasing forward bias, the *tunnel effect* contribution becomes small and as a result



(*a*) Circuit symbol

(*b*) *VI*-curve of a tunnel diode

Figure 4.7

negative resistance region is produced on the diode characteristic. Further increase in the bias voltage, producing V-I curve like that of an ordinary PN-junction, as shown in Fig. 4.7(b). Tunneling occurs in both forward and reverse directions near to zero voltage ($V \neq 0$).

In tunnel diode, for very small bias voltage (of the order of 0.1 V), a very thin depletion layer exists to produce electric field near junction, which in turn induces Zener breakdown. Thus forward current increases fast with increasing bias until the depletion width becomes narrower and finally diffused. *Zener effect* then gradually ceases and current decreases as shown by the BC segment of the characteristic curve Fig. 4.7(b). This continues until the current reaches a value equal to ordinary forward bias current represented by CD region. Most important region in the curve is BC where current decreases with increasing voltage. This negative resistance region can be used to design high frequency (microwave) oscillators. In addition to peak voltage V_P and valley voltage V_V, two parameters are peak current I_P and valley current I_V, which can be used to specify the diode characteristic. For example, ratio of peak-to valley current of GaAs diode is 12 : 1 (Typical value).

Figure 4.8 shows the energy band diagram and Fermi energy level at three points of VI-curve of tunnel diode.

When no bias is applied, structure behaves like a resistor. Fermi energy levels on both sides are at the same level (height) and energy possessed by the electrons on the N-side is not enough to jump over the junction barrier to reach P-side. Quantum mechanically some electrons can tunnel the barrier in the given condition provided there are allowed empty states on the P-side. This condition is not satisfied. Hence forward current is zero.

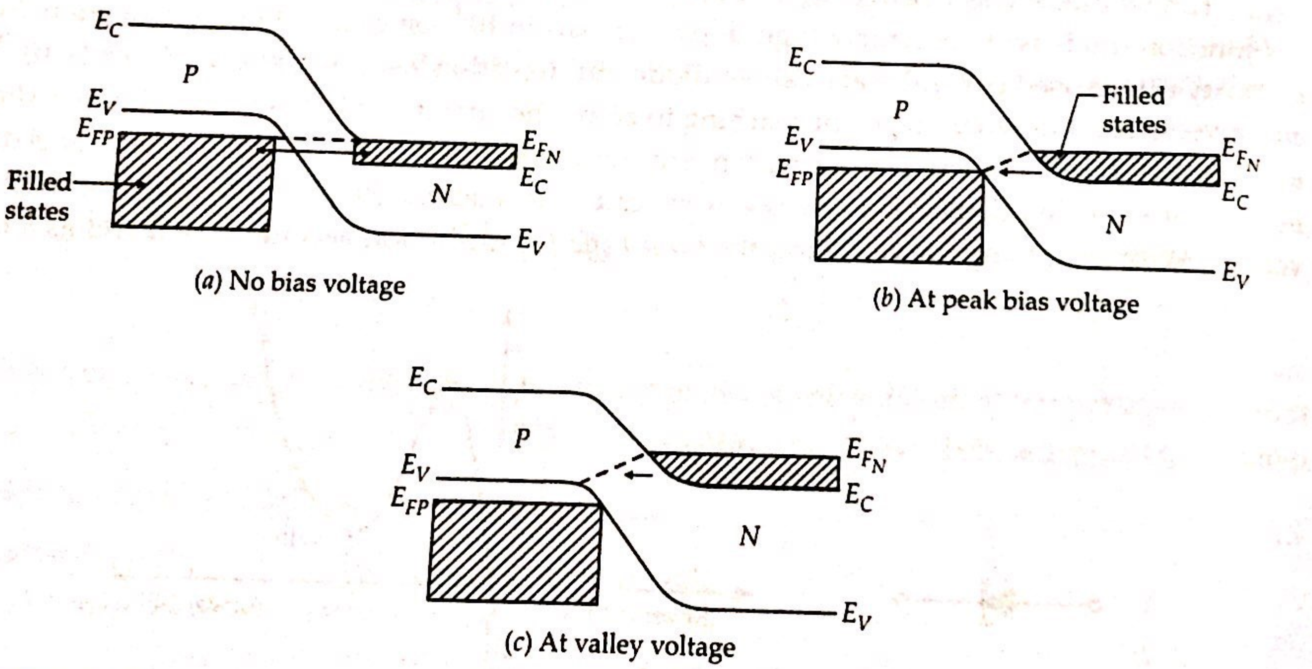


Figure 4.8 Band diagram and Fermi energy level.

As forward bias is applied about 0.1 V, filled states on the N-side are shifting upward, as a result higher energy electrons on N-side see empty states on the P-side. Hence tunneling begins from N to P-side. Peak current flows because of necessary conditions for tunneling (thin barrier, equally filled and empty states) are satisfied as shown in Fig. 4.8(b).

If the forward bias is increased beyond peak voltage tunneling will decrease as visualised in Fig. 4.8(*c*). The Fermi level on *N*-side shifted upward, result in very small filled states on *N*-side are lined up with any empty state on *P*-side. This means that the current flows in very small amount and is known as *valley current*, I_V.

Applications. Tunnel diodes have numerous applications, some of them are :

(*i*) As an amplifier.

(*ii*) As microwave oscillator due to its negative resistance.

(*iii*) Used as ultrahigh speed switches because tunneling is much faster than the normal crossing of electrons.

Tunnel diodes are low cost, low noise, simple, compact, low power and high speed devices. It operates below 1 V, therefore any fluctuations in the voltage may lead to burn or damage the device.

4.6 Photodiode

A photodiode is a semiconductor device that converts light into current. A *PN*-junction diode is usually sealed in a transparent plastic so that its junction region may be exposed to light of suitable intensity and frequency. It is operated in the reverse bias as shown in Fig. 4.9. In absence of light, very small reverse saturation current flows due to minority carriers, known *as dark current*. When light falls on the depletion region ($h\nu \geq \Delta E_g$ forbidden gap), light energy photons get absorbed by the bound electrons of immobile ions, new electron-hole pair generated. These newly generated electrons moved towards the *N*-side and holes towards the *P*-side by the reverse bias. As a result large reverse current flows through the junction diode, known as *photo-current*.

The photo-current is proportional to the intensity of light. Photodiodes can be used in several circuits *e.g.*, light controlled relays, counter, optical reader and light metering etc.

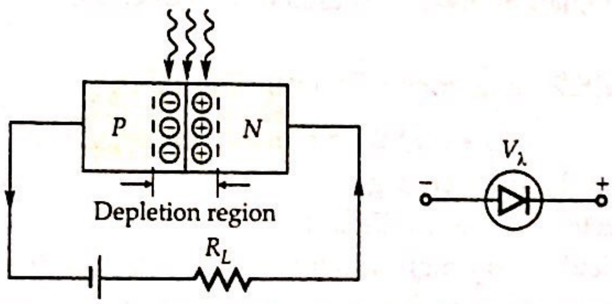


Figure 4.9 A photodiode circuit and symbol.

4.6.1 PIN Photodiode

It acts as a receiver or detector of light at the output end of the optical fibre. It detects and converts optical signal to electrical signal. Typical photo-detectors are *PN*-junction (discussed earlier), positive intrinsic negative (PIN) photodiode and Avalanche Photodiode (APD).

PIN photodiode is modified version of standard *PN*-junction diode in which thick intrinsic (pure or lightly doped) semiconducting layer is inserted between thin *P* and *N* regions. The large resistance of intermediate intrinsic layer provides larger electric field between *P* and *N* regions and therefore, charge carriers drift towards their majority carrier side. This enhances faster response of the diode, enabling them to operate at frequencies greater than 300 MHz (microwave region).

Under forward bias condition, PIN diode offers a variable resistance, which decreases with the forward current and behaves like a short circuit whereas in reverse bias it acts like open circuit due to its infinite resistance. The circuit diagram for a PIN photodiode is shown in Fig. 4.10, which is reverse biased.

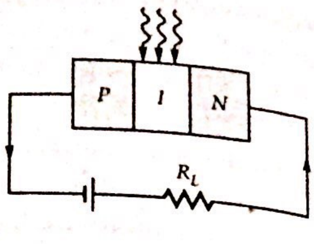


Figure 4.10 A PIN photodiode circuit.

When reverse bias is applied and increases gradually, width of depletion region increases, at a certain reverse voltage, width extends to the almost entire region of intrinsic layer. Now region of intrinsic layer becomes the absorption region where most of the absorption of light photon occurs. Depletion of free carriers in a region provides only immobile ions, that absorb the photons to emit free electrons. So the width of depletion region plays very important role in electron-hole pair production. In most microwave applications, sweeping out of intrinsic (*I*) region is necessary otherwise the current flow due to mobile carriers in high resistivity *I*-region will be source of signal loss. So the PIN diodes, when used in microwave switches are reverse biased. The reverse current flowing in the circuit is directly proportional to the illumination of light. In the PIN photodiode, transit time of carriers is small because of large width of depletion region, results in achieving high quantum efficiency. Such diodes have faster response time due to lower value of capacitance between *P* and *N* regions ($C_T = \frac{\varepsilon A}{d}$, *d* is the thickness of the depletion layer, *A* is area of *PN*-junction, ε is the permittivity of semiconducting material).

4.6.2 Avalanche Photodiode (APD)

It is a slightly modified version of PIN photodiode as shown in Fig. 4.11. Light photons fall on the intrinsic region of the structure and cause the generation of electron–hole pairs. Under the action of electric field the electron moves towards the *PN*-junction depletion region. Here electric field is very high which causes the electron to gain very high velocity and collide with the immobile ions, create new electron-hole pair. In this way a single electron produced by light in the intrinsic I-region, may create large number of electrons. This process is *cumulative multiplication* of free electrons under the action of a strong electric field, known as *Avalanche effect*. For this effect to happen, very high reverse bias voltage (in the order of 100-400 V) is required. A large number of liberated electron-hole pairs contribute to the current in the external circuit whose magnitude is proportional to the intensity of light incident on the APD.

The avalanche photodiode is more sensitive than the PIN photodiode. It is also found that APD is non-linear and as a result output signal is far noiser than one obtained from a PIN photodiode. Here current gain depends on the bias voltage and thermal fluctuations. Therefore device must be kept on an adequate heat sink.

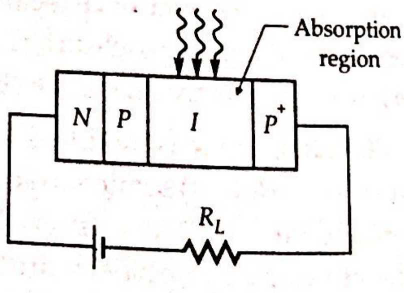


Figure 4.11 Structure of Avalanche Photodiode.

4.7 Light Emitting Diode (LED)

The LED emits visible light of a wavelength when a current is passed through the forward biased *PN*-junction diode as visualised in Fig. 4.12. The mechanism is just reverse to that of a photo- diode. Here electric current (electrons) converted into light (visible or invisible).

A free electron in the conduction band recombines with a free hole in the valence band by crossing the barrier at the *PN*-junction. In the process of recombination, electromagnetic radiation of energy equals to the band gap of the semiconducting material is released. Some semiconducting materials like GaAs, GaP, GaAsP etc. have band gap (ΔE_g) energy in the range of about 1.5 – 3.0 eV, which provides radiations in the visible/infrared region. Frequency of emitted radiation can be calculated by

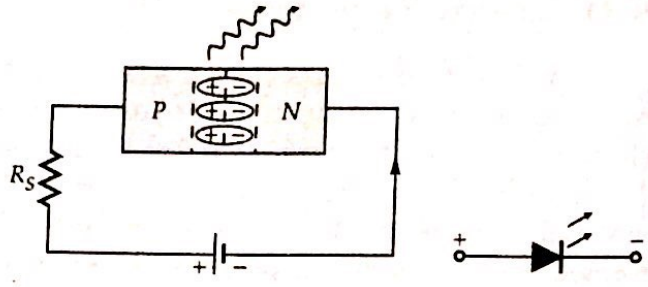


Figure 4.12 LED and its circuit symbol.

$$\nu = \frac{\Delta E_g}{h} \quad ...(4.8)$$

where h is Planck's constant and its value is 6.67×10^{-34} Js.

The intensity of the light emitted due to recombination process is directly proportional to the rate of (electron-hole) recombinations at the junction.

Light emitting diodes (LEDs) are widely used in small indicator, warning lights and in alphanumeric display devices (like calculators) etc. LEDs with invisible radiation may find applications in remote control devices, burglar alarm system etc.

In normal *PN*-junction diode (consists of Si or Ge), connected in forward bias, radiation produced at the junction due to electron-hole pair recombination is in the form of heat (IR radiation). Operation of LED ceases, if it is reverse biased and eventually LED may get destroyed.

Seven-Segment Display

Figure 4.13 shows a seven-segment display with schematic diagram. It has seven LEDs (*A* to *G*). Each LED is called a segment.

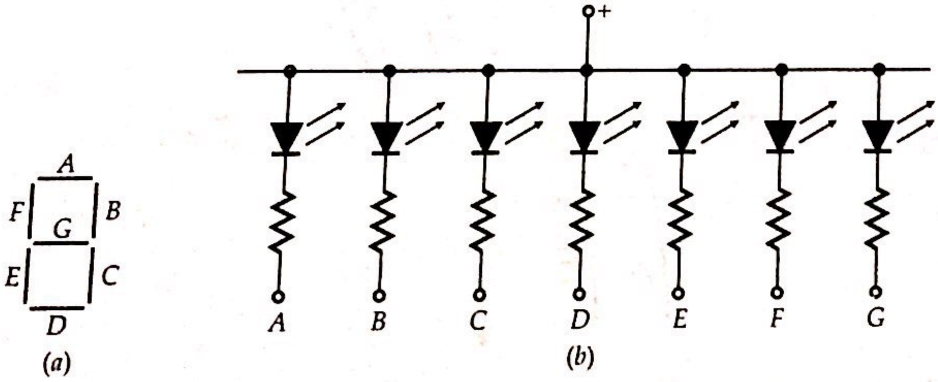


Figure 4.13 (*a*) Seven-Segment Display (*b*) Schematic Diagram

Here external resistors are used to control the current to safe levels. We can form any digit (0 to 9), capital letters (*A, C, E, F*) and small letters (*b* and *d*).

Example. By considering *A, B* and *C* LEDs, we can form 7.

Typical value of forward voltage for a TTL 222 LED (green) varies from 1.8 V to 3 V for a current of 25 mA.

4.8 Schottky Barrier Diode

A diode consisting of a metal semiconductor (Schottky barrier) as shown in Fig. 4.14, which has *VI*-characteristic curve similar to ordinary *PN*-diode. It is unipolar device because it has only electrons as majority carriers on both sides of the junction. A Schottky diode differs from a *PN*-junction diode in that the diode forward voltage is lower (0.20 V–0.25 V) for commonly used materials. In this diode no depletion layer is formed near the junction because of unipolar carriers (electrons). As a result no charge stored when it is operated in forward bias. The device can be switched off faster than the bipolar diodes by the application of reverse bias as charge storage time is negligible. Under reverse bias, no significant current flows through the diode.

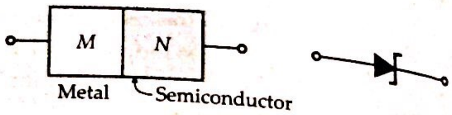


Figure 4.14 Schottky diode and its circuit symbol.

Schottky diode offers a lower resistance in forward bias due to large contact area between the metal and semiconductor in comparison to point contact. When forward bias is applied, electrons on the *N* side gain sufficient energy so that it crosses the barrier and enters into the metal region. These high energy electrons are known as *hot carriers* and diode is called as *hot carrier diode.*

The reverse recovery time is so short that they can be used in switching power supplies at 20 GHz frequencies. These diodes can rectify the signals of frequencies upto 300 MHz. Most important application of Schottky diodes is in digital computers, where computer speed depends on how fast its diodes and transistors can switch ON and OFF.

Figure 4.15 shows a comparison of *VI*-characteristic of Schottky and *PN*-unction diodes. Schottky diode has a lower barrier potential than the ordinary *PN*-junction diode.

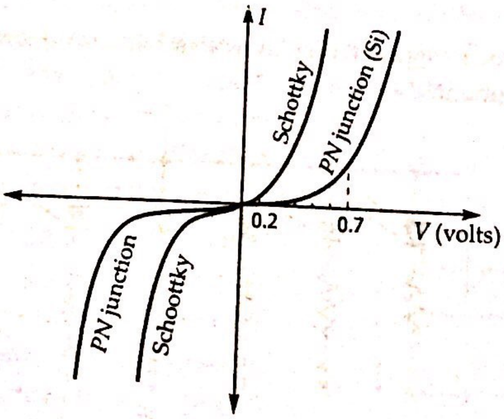


Figure 4.15 Comparison of *VI*-characteristic curves of Schottky and Si *PN*-junction diode.

4.9 Gunn Diode

High speed semicondu
semiconductor) and PIN dio
region) such as mixers, detec

Gunn diodes are also k
and can be used as low pow

Gunn discovered the
(GaAs), indium phosphide
have closely spaced energy
in Fig. 4.16. When electric fi
At low voltage, most of the
certain level so that elect
more than the thresho
transferred into the upper
effective mass is higher in
than lower valley and hen
becomes lower than that
Since conductivity is dire
the mobility, as a result co
decreases with an incre
(electric field) across the r
called *transferred electron*
referred as *Gunn effect*. A
(≈3300 V / cm), semico
(mentioned above) show
over a range of voltages
Therefore, device can b
oscillators.

The circuit diagr
Fig. 4.18.

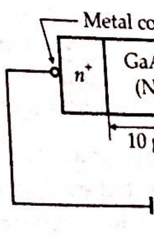


Figure 4.17 Gunn diode

4.9 Gunn Diode

High speed semiconducting diodes are Varactor, Gunn, tunnel, IMPATT, Schottky (metal + semiconductor) and PIN diodes. These devices find applications in microwave region (GHz region) such as mixers, detectors, receivers and switches etc.

Gunn diodes are also known as *transferred electron devices*, having negative resistance region and can be used as low power oscillators at microwave frequencies.

Gunn discovered the microwave oscillation in indium arsenide (InAs), gallium arsenide (GaAs), indium phosphide (InP) and cadmium telluride (CdTe) in 1963. These semiconductors have closely spaced energy valleys in conduction band named as lower and upper valley as shown in Fig. 4.16. When electric field (dc) is applied across these materials, electric field set up across it. At low voltage, most of the electrons are situated in the lower valley but as voltage exceeds the certain level so that electric field becomes more than the threshold, electrons get transferred into the upper valley. Electron's effective mass is higher in the upper valley than lower valley and hence electron mobility becomes lower than that of the lower valley. Since conductivity is directly proportional to the mobility, as a result conductivity (current) decreases with an increase in the voltage (electric field) across the material. This effect is called *transferred electron effect* or commonly referred as *Gunn effect*. After threshold voltage ($\approx 3300\, V/cm$), semiconducting materials (mentioned above) show negative resistance over a range of voltages as shown in Fig. 4.18. Therefore, device can be used in microwave oscillators.

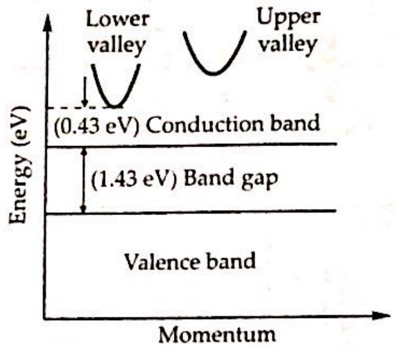


Figure 4.16 Energy diagram of GaAs.

The circuit diagram of Gunn diode is shown in Fig. 4.17 and *VI*-characteristic is shown in Fig. 4.18.

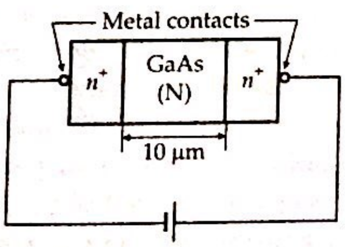


Figure 4.17 Gunn diode

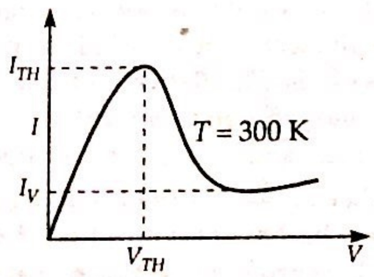


Figure 4.18 *V-I* characteristic of GaAs.

4.10 IMPATT Diode

IMPATT is abbreviation of IMPact ionization Avalanche Transit-Time. It is a high power diode used in high frequency electronics and microwave devices. IMPATT can operate at frequencies between 3 to 100 GHz or above. It can withstand power more than 10 W. There are several advantages of IMPATT diode like high efficiency, high operating frequency and least noise. Main practical application of this diode is in microwave power generators.

The most commonly used materials for IMPATT diodes are silicon (Si) and gallium arsenide (GaAs). Other materials like germanium (Ge), indium phosphide (InP), gallium aluminium phosphide (GaAlP) can also be utilized in the construction. There are different forms of IMPATT structures. For example, P^+-N-I-N, P^+-I-N^+, P^+-N-N^+ etc. (P^+ and N^+ stand for heavily doped P and N regions respectively.

Let us consider the third structure (P^+-N-N^+) as shown in Fig. 4.19 along with electric field profile. Shaded region shows the area of breakdown region.

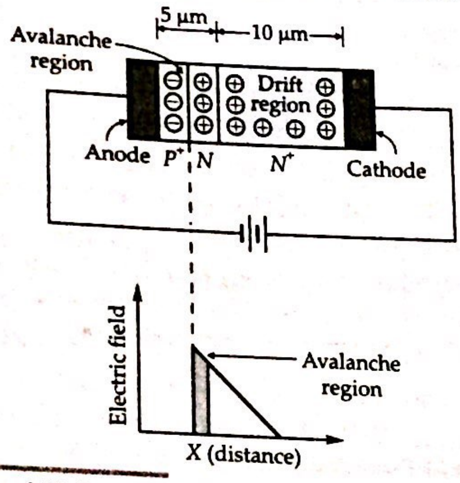


Fig. 4.19 IMPATT diode structure with electric field profiles.

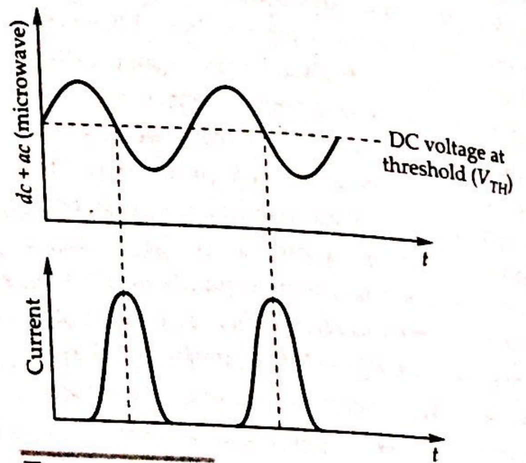


Figure 4.20 IMPATT diode voltage and current waveforms.

The diode utilizes Avalanche breakdown with the transit time of the carriers to provide a negative resistance region, thus acts as oscillator amplifier. IMPATT diode is reverse biased, at a certain reverse voltage Avalanche breakdown occurs like in normal PN-junction diode. Electric field at PN-junction is very high because voltage drop appears across a very thin depletion region. Under breakdown condition, minority carriers get accelerated, as a result they collide with the crystal lattice (immobile ions) and new hole-electron pairs are generated. These newly carriers again accelerated due to high electric field, collide with the lattice producing more (hole-electron) charge carriers. This process is cumulative and referred as avalanche breakdown. Avalanche region produces electrons and holes and drift region provides space for their motion. Carrier takes some time to reach the terminals, which is dependent upon the thickness of the drift region termed as transit time.

When an electric field is applied the current peaks are found to be out of phase (180°) with the voltage because of transit time delay. The thickness of drift region is selected so that the time taken by the current pulse to arrive at the cathode corresponds to a further 90° phase difference. As shown in Fig. 4.20, when a.c. current arrives at the cathode, a.c. voltage there is at its negative peak. Thus voltage and current in the IMPATT diode are out of phase.

Formulae at a Glance

4.1 Zener diode is a specially designed diode optimized for operation in breakdown region. For breakdown operation :

(*i*) $V_{TH} > V_Z$

where V_Z = Zener voltage

and $V_{TH} = \left(\frac{R_L}{R_L + R_S}\right) . V_{in}$

(*ii*) Total current, $I_S = I_Z + I_L$

(*iii*) From series resistor and zener diode loop, KVL provides, $V_{in} = I_S R_S + V_Z$

(*iv*) $I_S = \frac{V_{in} - V_Z}{R_S}$

(*v*) Voltage drop across load resistor R_L

$$V_L = I_L . R_L$$

Hence $I_L = \frac{V_L}{R_L}$

(*vi*) In voltage regulating condition, $V_Z = V_L$

4.2 Maximum series resistance R_S :

$$(R_S)_{max} = \left(\frac{V_{in(min)}}{V_Z} - 1\right) R_{L(min)}$$

4.3 $(R_S)_{max} = \frac{V_{in(min)} - V_Z}{I_{L(max)}}$

4.4 Current through LED, $I = \frac{V_{in} - V_{LED}}{R_S}$

where R_S and LED are connected in series in forward biased.

4.5 Power dissipation through a Zener diode

$$P_Z = V_Z I_Z$$

4.6 Power rating of a Zener diode

$$P_{ZM} = I_{ZM} V_Z$$

where I_{ZM} is maximum rated zener current.

Miscellaneous Solved Numerical Problems

Problem 4.1 *What value of series resistance is required when three 10 W, 10 V, 1000 mA Zener diodes are connected in series to obtain a 30 V regulated output from a 45 V input supply ?*

Solution. Given : $V_{in} = 45\text{ V}$, $V_0 = 30\text{ V}$, $I_Z = 1000\text{ mA}$

The Zener diode's voltage regulator circuit is shown in Fig. 4.21.

To obtain 30 V output, all three diodes are connected in series reversed biased. Let output is open *i.e.*, $I_Z = I_S$ ($\because I_L = 0$)

$\therefore$ From Kirchhoff's voltage law ;

$$V_{in} = I_S R_S + V_{D_1} + V_{D_2} + V_{D_3}$$

$$\therefore \quad R_S = \frac{V_{in} - (V_{D_1} + V_{D_2} + V_{D_3})}{I_Z (= I_S)}$$

$$= \frac{45 - 30}{1000 \times 10^{-3}} = \frac{15 \times 10^3}{1000} = 15\Omega.$$

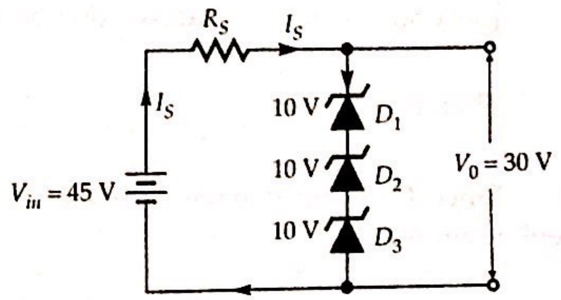


Figure 4.21

Problem 4.2 *Over what range of input voltage will the Zener circuit shown in Fig. 4.22 maintains a 30 V across 2 kΩ load, if $R_S = 200\,\Omega$ and $(I_Z)_{max.}$ i.e., Zener current rating is 25 mA ?*

Solution. Given $(I_Z)_{max} = 25$ mA, $R_L = 2$ kΩ, $R_S = 200\,\Omega$

(*i*) To get minimum input voltage, I_Z should be minimum and I_L should be maximum.

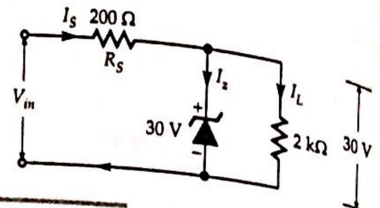


Figure 4.22

Therefore, let $I_Z = 0$,

$$I_S = I_L = \frac{30}{2\times10^3} = 15\text{ mA}$$

Ohm's law : Voltage drop across R_S,

$$V_S = I_S \times R_S = 15\times10^{-3}\times200 = 3\text{ V}.$$

Therefore, from KVL, $(V_{in})_{min.} = V_S + V_Z = 3+30 = 33$ V.

(*ii*) Similarly, to get maximum input voltage, I_Z should be maximum and I_L should be minimum. Since I_L is fixed = 15 mA

∴ Total input current $\quad I_S = I_L + (I_Z)_{max.} = 15+25 = 40$ mA

Therefore, from KVL, $V_{in(max.)} = V_S + V_Z = I_S R_S + V_Z = 40\times10^{-3}\times200+30 = 38$ V

Thus, V_{in} ranges from 33 to 38 V to maintain 30 V across the load.

Problem 4.3 *Is the Zener diode of Fig. 4.23 operating in the breakdown region ? If yes then calculate (i) I_S (ii) I_L (iii) I_Z.*

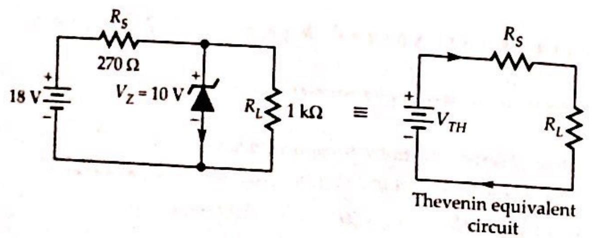


Figure 4.23

Solution. Yes the Zener diode of Fig. 4.23 is operated in breakdown region.

(*i*) Condition for breakdown operation $V_{TH} > V_Z$.

Therefore $\quad V_{TH} = \left(\frac{R_L}{R_L+R_S}\right).V_{in} = 14.2$ V

Since Thevenin voltage is greater than Zener voltage, the Zener diode is operating in the breakdown region.

$$I_S = \frac{V_{in}-V_Z}{R_S} = \frac{18-10}{270} = 29.6\text{ mA}$$

(*ii*) Load current $\quad I_L = \frac{V_L(=V_Z)}{R_L} = \frac{10}{10^3} = 10$ mA

(*iii*) Zener current, $I_Z = I_S - I_L = 29.6-10 = 19.6$ mA

Problem. 4.4 *For the Zener diode of Fig. 4.24, find (a) the output voltage (b) voltage across R_S and (c) current through Zener.*

Solution. If Zener diode operates in breakdown region.

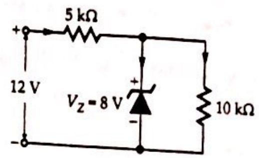


Figure 4.24

Condition is $V_{TH} > V_Z$

where $\quad V_{TH} = \left(\frac{R_L}{R_L+R_S}\right).V_{in} = \left(\frac{10}{10+5}\right).12 = 8.0$ V

and $\quad V_Z = 8$ V $\quad ∴ \quad V_{TH} = V_Z = 8$ V.

The Zener does not operate in the breakdown region and behaves like open circuit *i.e.*, $I_Z = 0$.

(*a*) The output voltage $V_0 = V_{TH} = 8$ V

(*b*) Voltage across R_S, $V_S = V_{in} - V_o = 12-8 = 4$ V (KCL)

(*c*) Zener current, $I_Z = 0$ mA

Problem 4.5 *A Zener diode as shown in Fig. 4.25 regulates at 75 V from 10 to 100 mA current. The supply voltage is 180 V. Calculate the value of resistance R_S to allow voltage regulation from $I_L = 0$ to $I_L = I_{L(max)}$. What is $I_{L(max)}$, if R_S is set as above but I_L is fixed at 40 mA ? Find the permissible range of V_b.*

[GGSIPU, Dec. 2013(6 marks)]

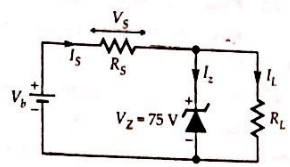


Figure 4.25

Solution. Given $V_{in} = 180$ V, $I_Z = 75$,

$$I_{Z(min)} = 10\text{ mA},\ I_{Z(max.)} = 100\text{ mA}$$

(*i*) *Determination of R_S*. Since Zener is operated in breakdown region with

$$I_{Z(min.)} = 10\text{ mA},\ I_{Z(max.)} = 100\text{ mA and } V_Z = 75\text{ V}.$$

When $I_{L(min.)} = 0$, Zener current will be maximum, $I_{Z(max.)} = 100$ mA

Thus total current, $\quad I_S = I_{Z(max.)} + I_{L(min.)} = 100$ mA

KVL, $\quad V_S = V_{in} - V_Z = 180-75 = 105$ V.

From Ohm's law, we have $\quad I_S = \frac{V_S}{R_S}$ or $R_S = \frac{V_S}{I_S} = \frac{105}{100\times10^{-3}} = 1.05$ kΩ.

$$R_S = 1.05\text{ k}\Omega.$$

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(ii) Determination of $I_{L(max)}$. We know, total current $I_S = I_{Z(min)} + I_{L(max)}$

$\therefore \quad I_{L(max)} = I_S - I_{Z(min)} = 100 - 10 = 90\text{ mA}$

(iii) Determination of range of V_b. Here $I_L = 40$ mA is fixed.

$\therefore$ $V_{b(min)}$ will be obtained when minimum Zener current $I_{Z(min)} = 10$ mA will flow and $V_{b(max)}$ will be obtained for maximum $I_{Z(max.)} = 100$ mA.

$$\therefore \quad V_{b(min)} = V_S + V_Z = [I_{Z(min)} + I_L] \times R_S + V_Z$$

$$= (10 + 40) \times 10^{-3} \times 1.05 \times 10^3 + 75 = 127.5\text{ V}$$

Similarly, $V_{b(max)} = V_S + V_Z = [I_{Z(max)} + I_L] \times R_S + V_Z$

$$= (100 + 40) \times 10^{-3} \times 1.05 \times 10^3 + 75 = 222\text{ V}.$$

Therefore V_b varies from 127.5 V to 222 V.

Conceptual Questions

4.1 *What is a Zener diode ?*

Ans. A highly doped *PN*-junction diode which is specially designed for reverse bias operation and used as a voltage regulator.

4.2 *How does Zener diode act as voltage regulator ?*

Ans. *V-I* characteristics of Zener diode in reverse breakdown region show that almost a constant voltage drop occurs across the Zener diode, regardless of value of Zener current. This property is utilized in Zener voltage regulator.

4.3 *What are Zener and Avalanche effects ?*

Ans. *Zener Effect.* Due to large electric field at the junction, direct rapture of covalent bond occurs. Here depletion width is very small due to high doping ($V_Z < 6$ V).

Avalanche Effect. Minority carriers across the depletion region accelerate due to high external voltage in reverse biased. As a result, minority carriers hit and break the covalent bond. This process is cumulative and large number of electron-hole pairs generated ($V_Z > 6$ V).

4.4 *Whether Zener diode works in forward biased ?*

Ans. Yes, it behaves like normal *PN* junction diode in forward bias.

4.5 *What are the applications of Zener diode ?*

Ans. It can be used as voltage regulator, waveform clipper/voltage shifter etc.

4.6 *What is Varacter diode ?*

Ans. Specially designed diode in which junction capacitance changes with reverse applied voltage, known as voltage controlled capacitor or varicap.

4.7 *How does capacitance change with the voltage in Varactor diode ?*

Ans. Junction capacitance of a *PN*-junction diode is inversely proportional to the square root of reverse bias voltage (for alloyed junction) and cube root of reverse bias voltage for diffused junction.

4.8 *What are the applications of varicaps ?*

Ans. They are used in tuning circuit, phase locked loop (PLL) and frequency locked loop (FLL) circuits.

4.9 *What is tunnel diode ?*

Ans. The tunnel diode is a heavily doped (1 part in 10^3) *PN*-junction diode having negative resistance region in *VI*- characteristic curves.

4.10 *What do you mean by tunneling effect ?*

Ans. A highly doped semiconductor provides large number of carriers. When *PN*-junction is formed these carriers drift across the junction and a very thin depletion layer is produced under the action of a very small external positive potential, electrons can tunnel the potential barrier with very high speed. Thus a large current flows. This is known as tunneling effect.

4.11 *What are applications of tunnel diodes ?*

Ans. They are used in microwave generator, amplifiers and switching device because of very fast response of the carriers.

4.12 *Define photodiode.*

Ans. A photodiode is a reverse biased *PN*-junction diode which converts light energy into electrical energy.

4.13. *What are applications of photodiode ?*

Ans. They can be used in alarm circuit, counter circuit, optical power meters etc.

4.14 *What is Schottky diode ?*

Ans. It is different from normal *PN*-junction diode. It has metal on one side and *N*-type semiconductor on the other side. Metal acts as anode and *N*-type material acts as cathode. As soon as a small forward potential is applied (0.5 to 0.7 V), hot carrier electrons present in the N-side plung into metal. This process is very fast.

4.15 *What is reverse recovery time in Schottky diode ?*

Ans. In normal *PN*-junction, when diode switches from ON to OFF state, it takes about 100 n while in Schottky diode this time is about 100 ps because of no depletion region at the junction.

4.16 *What are the applications of Schottky diodes ?*

Ans. They are very useful in RF detectors, mixers, switch mode power converter etc.

4.17 *What is IMPATT diode ?*

Ans. It is a high power diode used in microwave region *i.e.*, in the frequency range from : 100 GHz. It is useful in microwave generation.

4.18 *What is main drawback of IMPATT diode ?*

Ans. Very high phase noise.

4.19 ***Explain LED in brief. What are the merits of LED ?*** **[GGSIPU, Nov. 2013 (2 marks)]**

Ans. Certain *PN*-junction diode, consists of material like GaAs, GaP, GaAsP etc., when connected in forward biased can produce light in visible or in IR region.

It happens due to recombination of electron-hole at the junction. LEDs can be used in displays, power indicators, lightings etc.

4.20 ***Explain photodiode with its symbol, operation and applications.*** **[GGSIPU, Nov. 2013(3.5 marks)]**

Ans. A photodiode is a semiconductor *PN*-junction diode that converts light into current. Usually operated in reverse biased. At zero bias, a small current (dark) is obtained. When light falls on the junction electrons hole-pair is generated producing large current.

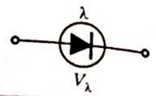

Figure 4.26 Circuit symbol of Photodiode.

It is used in alarm system, optical readers and light metering devices.

4.21 ***What are Gunn diodes and their applications ?***

Ans. Gunn diodes are also called transferred electron device (TED). Usually consist of GaAs or GaN, with two heavily doped *N*-type on each terminal and a thin lightly doped material in between. They are used in electronic oscillators to generate microwaves, in applications such as microwave relay transmitter, radar speed guns etc. They have negative resistance region in their *VI*-characteristic curves.

EXERCISE

Theoretical Questions

4.1 Explain Zener diode characteristics, Zener voltage, Zener current and dynamic resistance.

4.2 Explain Avalanche breakdown and Zener breakdown.

4.3 Explain the function of Zener diode and draw its *VI*-characteristic curve in all possible regions.

4.4 Explain that the Zener diode can act as a voltage regulator.

4.5 What is varacter diode ? Explain the reverse biased *PN* junction diode as a variable capacitor.

4.6 Explain the construction and working of a Schottky diode. Why Schottky diode is called as hot carrier diode ?

4.7 Draw the *VI*-characteristic curve of a tunnel diode and explain the negative resistance region on the basis of energy band diagram. **[GGSIPU, Dec. 2013(5 marks)]**

4.8 Explain Varactor diode giving its symbol, operation and applications. **[GGSIPU, Dec. 2013(2.5 marks)]**

4.9 What are the applications, advantages and disadvantages of a tunnel diode ?

4.10 Using proper diagram, explain the structure and working of APD.

4.11 What is IMPATT diode ? Show that it has negative resistance.

4.12 How does a LED work ? Describe its main applications which are useful in daily life.

4.13 Explain construction, working and *V-I* characteristics of a LED. **[GGSIPU, Dec. 2013(4 marks)]**

Numerical Problems

4.1 What value of series resistor is required to limit the current through a LED to 20 mA, with a forward voltage drop of 1.6 V, when connected to a 10 V supply ?

Hint. (*i*) Supply should be forward biased for LED operation.

(*ii*) In order to control the current through LED a resistor in series is required.

(*iii*) $R_S = \frac{V_{in} - V_{LED}}{I_{LED}} = \frac{10 - 1.6}{20 \times 10^{-3}} = 420\ \Omega$.

R_S is called current-limiting resistor.

4.2 The LC tank circuit has a 1 mH inductor. The varactor diode has capacitance of 100 pF when connected to reverse bias of 5 V. Determine the resonant frequency of this circuit for this reverse bias.

Hint. (*i*) Resonant frequency, $f = \frac{1}{\sqrt{2\pi LC}}$

(*ii*) $L = 1$ mH and $C = 100$ pF, $f = 503.3$ kHz.

4.3 Determine V_{R_S}, I_Z and V_L for Fig. 4.27.

Hint. (*i*) $V_{R_S} = V_{in} - V_Z = 6$ V

(*ii*) $I_Z = ?$ (Refer to Problem 4.4 at page 163)

(*iii*) $V_L = V_Z = 10$V

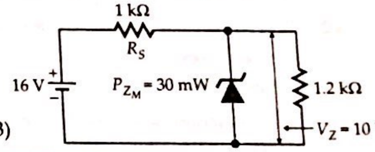

Figure 4.27

4.4 A varactor diode with a linearly graded doping profile has a capacitance of 40 pF, when no bias is applied to the diode. Determine the junction capacitance of the silicon diode (Si) when the reverse bias to the diode is of 7 V.

Hint. $C_T(V) = \frac{C_T(0)}{\left(1 + \frac{V_R}{V_K}\right)^{1/3}} = 22.48$ pF, where $C_T(0) = 40$ pF, $V_K = 0.6$ V, $V_R = 7$ V.

4.5 A Zener diode is specified as having a breakdown voltage of 9.1 V, with a maximum power dissipation of 364 mW. What is the maximum current the diode can handle ? **[Ans. 40 mA]**

4.6 Determine the range of input voltage applied to a Zener circuit to maintain 30 V across a load resistor of 2 kΩ. If $R_S = 200\ \Omega$ and Zener current rating is 25 mA. **[Ans. 33 to 38 V]**

4.7 A 10 V Zener diode is used to regulate the voltage across a variable load resistor taking current 10 to 85 mA. The input voltage varies between 13 to 16 V. Calculate the value of R_S if minimum Zener current is 15 mA. **[Ans. 30 Ω]**

4.8 For the circuit shown in Fig. 4.28. Find the maximum and minimum values of Zener diode current. **[Ans.** $(I_Z)_{max} = 9$ mA and $(I_Z)_{min} = 1$ mA

4.9 For the given data $V_{in} = 20$V, $R_S = 5$kΩ, $V_Z = 9$V and $R_L = 1$kΩ. Determine (*a*) output voltage (*b*) voltage across R_S (*c*) current through the Zener diode.

[Ans. (*a*) 9 V (*b*) 11 V (*c*) $I_Z = 13$mA**]**

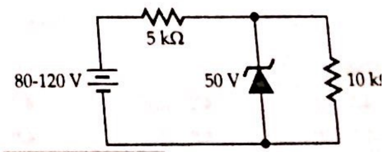

Figure 4.28