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CHAPTER 54

SPECIAL DIODES

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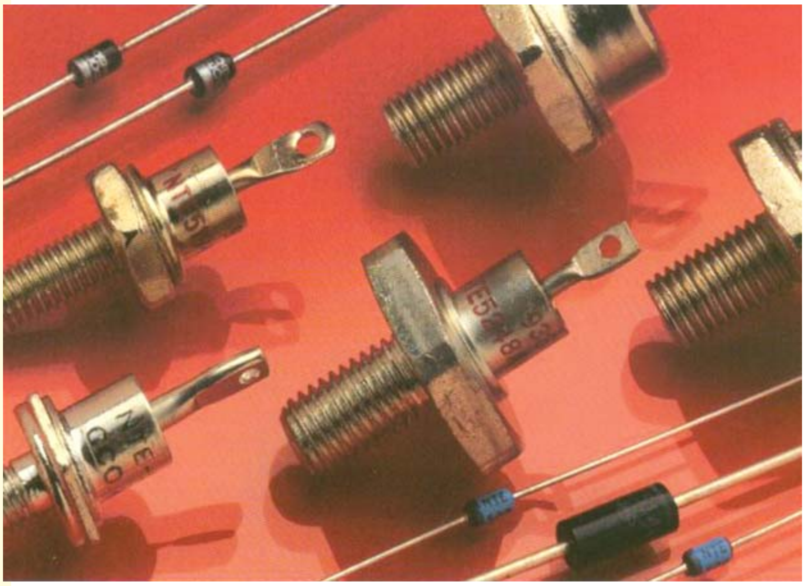

A major application for zener diodes is voltage regulation in dc power supplies. Zener diode maintains a nearly constant dc voltage under the proper operating conditions.

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54.1. Zener Diode

It is a reverse-biased heavily-doped silicon (or germanium) *P-N* junction diode which is operated in the ***breakdown region*** where current is limited by both external resistance and power dissipation of the diode. Silicon is perferred to Ge because of its higher temperature and current capability. As seen from Art. 52.3, when a diode breaks down, both Zener and avalanche effects are present although usually one or the other predominates depending on the value of reverse voltage. At reverse voltages less than 6 V, Zener effect predominates whereas above 6 V, avalanche effect is predominant. Strictly speaking, the first one should be called Zener diode and the second one as avalanche diode but the general practice is to call both types as Zener diodes.

Zener breakdown occurs due to ***breaking of covalent bonds by the strong electric field set up in the depletion region by the reverse voltage.*** It produces an extremely large number of electrons and holes which constitute the reverse saturation current (now called Zener current, I_z) whose value is limited only by the external resistance in the circuit. ***It is independent of the applied voltage.*** Avalanche breakdown occurs at higher reverse voltages when thermally-generated electrons acquire sufficient energy to produce more carriers by collision.

(*a*) V/I Characteristic

A typical characteristic is shown by Fig. 54.1 in the negative quadrant. The forward characteristic is simply that of an ordinary forward-biased junction diode. The important points on the reverse characteristic are :

V_z = Zener breakdown voltage

$I_{z\,min}$ = minimum current to sustain breakdown

$I_{z\,max}$ = maximum Zener current limited by maximum power dissipation.

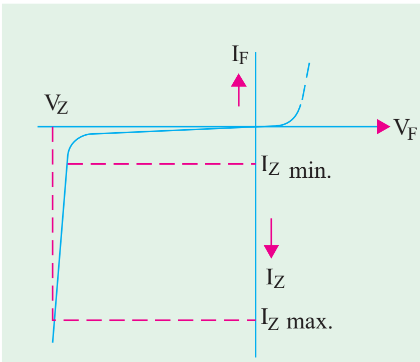


Fig. 54.1

Since its reverse characteristic is not exactly vertical, the diode possesses some resistance called ***Zener dynamic impedance****. However, we will neglect it assuming that the characteristic is truly vertical. In other words, we will assume an ideal Zener diode for which voltage ***does not change once it goes into breakdown.*** It means that V_z remains constant even when I_z increases considerably.

The schematic symbol of a Zener diode and its equivalent circuit are shown in Fig. 54.2 (*a*). The complete equivalent circuit is shown in Fig. 54.2 (*b*) and the approximate one in Fig. 54.2 (*c*) where it looks like a battery of V_z volts.

The schematic symbol of Fig. 54.2 (*a*) is similar to that of a normal diode except that the line representing the cathode is bent at both ends. With a little mental effort, the cathode symbol can be imagined to look like the letter *Z* for Zener.

(*b*) Zener Voltages

Zener diodes are available having Zener voltages of 2.4 V to 200 V. This voltage is temperature dependent. Their power dissipation is given by the product $V_z I_z$... maximum ratings vary from 150 mW to 50 W.

(*c*) Zener Biasing

For proper working of a Zener diode in any circuit, it is essential that it must

1. be reverse-biased;

2. have voltage across it greater than V_z;

* Its value is given by $Z_z = \Delta V_z / \Delta I_z$. It is negiligible as compared to large external resistance connected in the circuit.

3. be in a circuit where current is less than $I_{z\,max}$;

(*d*) Diode Identification

Physically, a Zener diode looks like any other diode and is recognized by its IN number such as IN 750 (10 W power) or IN 4000 (high power). Fig 54.2(*d*) shows a picture of a zener diode with V_z = 4.7V.

(*e*) Uses

Zener diodes find numerous applications in transistor circuitry. Some of their common uses are :

1. as voltage regulators;

2. as a fixed reference voltage in a network for biasing and comparison purposes and for calibrating voltmeters;

3. as peak clippers or voltage limiters;

4. for metre protection against damage from accidental application of excessive voltage;

5. for reshaping a waveform.

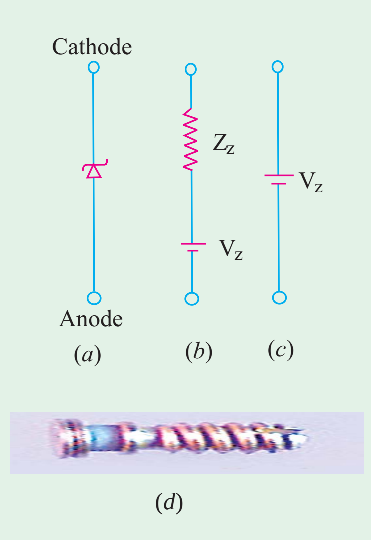


Fig. 54.2

Example 54.1. *Determine whether the ideal Zener diode of Fig. 54.3 is properly biased. Explain why ?*

Solution. Since positive battery terminal is connected to its cathode, the diode is reverse-biased.

Since applied voltage is less than V_z, the diode is not properly voltage-biased.

Example 54.2. *Find out if the Zener diode of Fig. 54.4 is properly-biased. If so, find diode current assuming it to be an ideal one.*

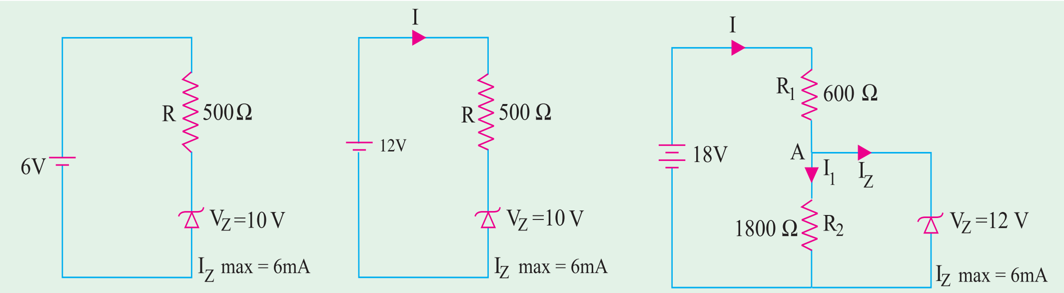


Fig. 54.3 Fig. 54.4 Fig. 54.5

Solution. Polarity-wise, the diode is properly-biased. Since applied voltage is greater than V_z, the diode is properly voltage-biased.

Drop across R = 12 – 10 = 2 V ∴ I = 2/500 = **4 mA**

Since this current is less than the maximum diode current, the diode is properly-biased according to the criteria laid down in Art. 54.1 (*c*).

Example. 54.3. *Determine if the Zener diode of Fig. 54.5 is biased properly. If so, find I_z and the power dissipated by the diode.*

Solution. Since its anode is connected to the negative battery terminal, the Zener diode is correctly reverse-biased.

Now, $V_{AB} = V_Z = 12$ V. Hence, drop across $R_1 = 18 - 12 = 6$ V

∴ I = 6/600 = 0.01 A = 10 mA

$I_1 = 12/1800 = 6.7 \times 10^{-3}$ A = 6.7 mA

$I_z = I - I_1 = 10 - 6.7 = 3.3$ mA

Since I_z is less than $I_{z\,max}$, the diode is properly-biased in every respect as per Art 4.1. Power dissipated = $V_z I_z = 12 \times 3.3$ = **39.6 mW.**

Example. 54.4. *Calculate the value of E_0 in the given circuit of Fig. 54.6. Given E_{in} = 6 V and 20 V.* **(Electrical Engg. II, Indore Univ.)**

Solution. When E_{in} is 6 V, the diode acts like an open circuit. It is so because 6 V is not enough to cause Zener break-down which will take place only when E_{in} exceeds 10 V. Hence, in this case, $E_0 = 0$.

When E_{in} = 20 V, breakdown occurs but voltage across diode remains constant at 10 V. The balance (20 − 10) = 10 V appears across 100 Ω resistor. Hence, E_0 = drop across R = **10 V.**

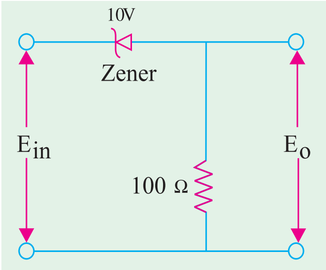


Fig. 54.6

54.2. Voltage Regulation

It is a measure of a circuit's ability to maintain a constant output voltage even when either input voltage or load current varies. A Zener diode, when working in the breakdown region, can serve as a voltage regulator. In Fig. 54.7, V_{in} is the input dc voltage whose variations are to be regulated. The Zener diode is reverse-connected across V_{in}. When p.d. across the diode is greater than V_z, it conducts and draws relatively large current through the series resistance R.

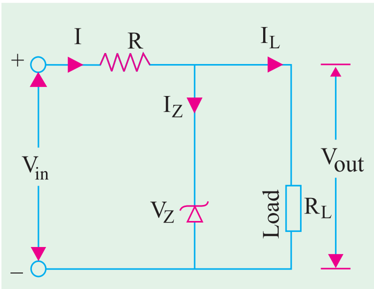


Fig. 54.7

The load resistance R_L across which a constant voltage V_{out} is required, is connected in parallel with the diode. The total current I passing through R equals the sum of diode current and load current *i.e.* $I = I_z + I_L$.

It will be seen that under all conditions $V_{out} = V_z$. Hence, $V_{in} = IR + V_{out} = IR + V_z$.

Case 1. Suppose R_L is kept fixed but supply voltage V_{in} is increased slightly. It will increase I. This increases in I will be absorbed by the Zener diode without affecting I_L. The increase in V_{in} will be dropped across R thereby keeping V_{out} constant. Conversely if supply voltage V_{in} falls, the diode takes a smaller current and voltage drop across R is reduced, thus againt keeping V_{out} constant. Hence, when V_{in} changes, I and IR drop change in such a way as to keep V_{out} (= V_z) constant.

Case 2. In this case, V_{in} is fixed but I_z is changed. When I_L increases, diode current I_z decreases thereby keeping I and hence IR drop constant. In this way, V_{out} remains unaffected.

Should I_L decrease, I_z would increase in order to keep I and hence IR drop constant. Again, V_{out} would remain unchanged because

$$V_{out} = V_{in} - IR = V_{in} - (I_z + I_L) R$$

Incidentally, it may be noted that $R = (V_{in} - V_{out}) / (I_z + I_L)$

It may also be noted that when diode current reaches its maximum value, I_L becomes zero. In that case

$$R = \frac{V_{in} - V_{out}}{I_{Zmax}}$$

In Fig. 54.7, only one reference voltage level is available. Fig. 54.8 shows the circuits for establishing two reference levels. Here, two diodes having different Zener voltages have been connected in series.

Example 54.5. *Calculate the battery current I, I_z and I_L in the circuit of Fig. 54.9. How will these values be affected if source voltage increases to 70 V? Neglect Zener resistance.*

(Industrial Electronics, Pune Univ.)

Solution. When V_{in} = **40 V**

Now, $V_{AB} = V_z = 10$ V

∴ I = 30/3 K = **10 mA**

∴ drop across 3K series (or line) resistor is = 40 − 10 = 30 V

$I_L = V_z/R_L = V_{AB}/R_L = 10/2$ K = **5 mA**

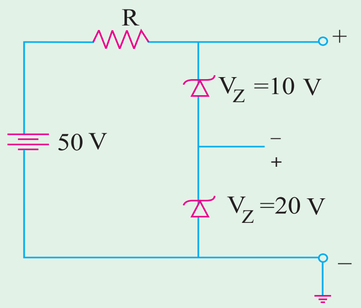


Fig. 54.8

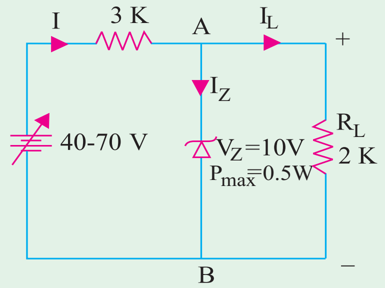


Fig. 54.9

∴ $I_z = I - I_L = 10 - 5 =$ **5 mA**

Now, $P_{max} = V_z . I_{z\,(max)}$ or $0.5 = 10 \times I_{z\,(max)}$

or $I_{z\,(max)} = 0.5/10 = 0.05$ A = 50 mA

Obviously, diode current of 5 mA is very much within the current range of the diode.

(*b*) When, V_{in} **= 70 V**

Drop across $R = 70 - 10 = 60$ V ∴ $I = 60/3$ K = **20 mA**

I_L = **5 mA** (as before); $I_z = I - I_L = 20 - 5 =$ **15 mA**

Example 54.6. *Using the ideal Zener approximations, find current through the diode of Fig. 54.10 when load resistance R_L is **(i)** 30 K **(ii)** 5 K **(iii)** 3 K.* **(Electronics, Madurai Kamraj Univ.)**

Solution. (*i*) R_L **= 30 K**

$V_{AB} = V_z = 30$ V ; drop across $R = 60 - 30 = 30$ V

∴ $I = 30/3$ K = 10 mA ; $I_L = V_{AB}/R_L = 30/30$ K = 1 mA

∴ $I_z = I - I_L = 10 - 1 = 9$ mA

(*ii*) When R_L **= 5 K**

I = 10 mA — as before ; $I_L = 30/5\ K$ = 6 mA $I_z = 10 - 6 =$ **4 mA**

(*iii*) When R_L **= 3K**

I = 10 mA — as before ; $I_L = 30/3$ K = 10 mA $I_z = I - I_L = 10 - 10 = 0$

In this case, it is obvious that the diode is just on the ***verge of coming out of breakdown region***. If R_L is reduced further, the diode will come out of breakdown region and would no longer act as a voltage regulator.

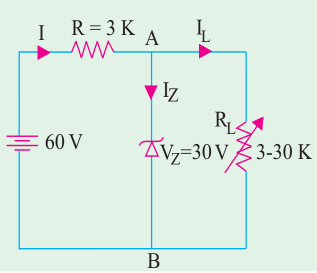


Fig. 54.10

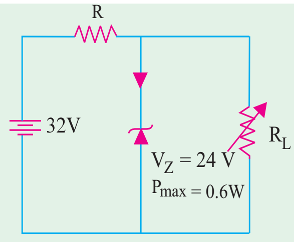


Fig. 54.11

Example 54.7. *A 24-V, 600-mW Zener diode is to be used for providing a 24-V stabilized supply to a variable load (Fig. 54.11). If input voltage is 32 V, calculate the **(i)** series resistance R required **(ii)** diode current when R_L = 1200 Ω.* **(Applied Electronics, Punjab Univ. 1991)**

Solution. (*i*) $V_z I_z(max)$ = 600 mW ; $I_{z(max)} = 600/24 = 25$ mA

$$\therefore \quad R = \frac{V_{in} - V_{out}}{I_{z\,(max)}} = \frac{32 - 24}{25 \times 10^{-3}} = \mathbf{320\ \Omega}$$

(*ii*) When R_L = 1200 Ω, $I_L = V_z/R_L = 24/1200 = 20$ mA; $I_z = 25 - 20 =$ **5 mA**

54.3. Zener Diode as Peak Clipper

Use of Zener diodes in wave-shaping circuits is illustrated in Fig. 54.12. The two similar diodes D_1 and D_2 have been joined back-to-back across the input sine wave voltage of peak value ± 25 V. Both have V_z = 20 V. As seen, the output is a semi-square wave with a peak value of ± 20 V.

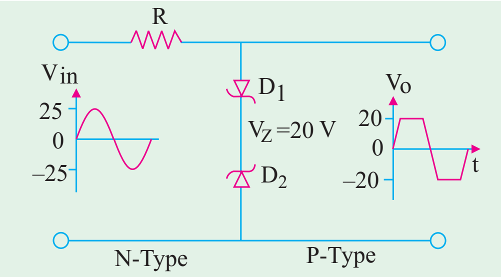


Fig. 54.12

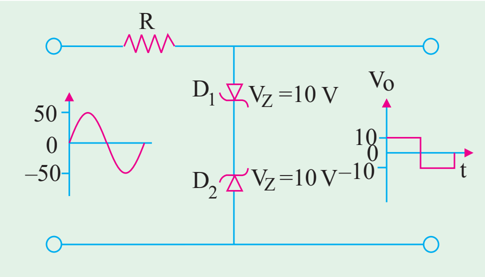


Fig. 54.13

It is well-known that a Zener diode acts like *a* 'short' (or very low resistance) in the forward direction and an 'open' in the reverse direction till it goes into breakdown at V_z. During positive input half-cycle, D_1 is shorted (being forward-biased) but D_2 acts like an open upto 20 V. Thereafter, it goes into breakdown and holds the output voltage constant till input voltage falls below 20 V in the later part of the half-cycle. At that point, D_2 comes out of the breakdown and again acts like an open across which the entire input voltage is dropped.

During the negative input half-cycle, roles of D_1 and D_2 are reversed. As a result, the output wave is clipped on both peaks as shown in Fig. 54.12.

If we increase the peak value of the input signal voltage and use Zener diodes of lesser V_z value, we can get an almost square output voltage wave from a sinusoidal input wave as shown in Fig. 54.13.

54.4. Meter Protection

Zener diodes are frequently used in volt-ohm-milliammeters (VOM) for protecting meter movement against burn-out from accidental overloads. If VOM is set to its 2.5 V range and the test leads are accidentally connected to a 25 V circuit, an unprotected meter will be burned out or at least get severely damaged.

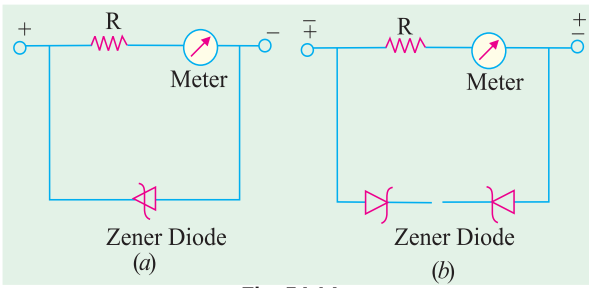


Fig. 54.14

This hazard can be avoided by connecting a Zener diode in parallel with the meter as shown in Fig. 54.14 (*a*). In the event of an accidental overload, most of the current will pass through the diode. Two Zener diodes connected as shown in Fig. 54.14 (*b*) can provide overload protection regardless of the applied polarity.

54.5. Zener Diode as a Reference Element

In many electronic circuits, it is desirable to maintain a constant voltage between two points and use it as a reference voltage for comparing other voltages against it. The difference between the two voltages is amplified and then used for performing some control function. This type of arrangement is used for power supply voltage regulator circuits, measurement circuits and servomechanism circuits. The constant-voltage characteristic in its breakdown region makes a Zener diode desirable for this application. Fig. 54.15 shows a circuit in which Zener diode is used as a reference element. The reference voltage equals the Zener breakdown voltage. The value of *R* is so chosen that the diode operates well within its breakdown region. The difference ($E_{in} – E_{ref}$) gives the control output.

54.6. Tunneling Effect

In a normally-doped P-N junction, the depletion layer is relatively wide and a potential barrier exists across the junction. The charge carriers on either side of the junction cannot cross over unless they possess sufficient energy to overcome this barrier (0.3 V for Ge and 0.7 V for Si). As is well-known, width of the depletion region depends directly on the doping density of the semiconductor. If a P-N junction is doped very heavily (1000 times or more)*, its depletion layer becomes extremely thin (about 0.00001 mm). It is found that under such conditions, many carriers can 'punch through' the junction with the speed of light even when they do not possess enough energy to overcome the potential barrier. Consequently, large forward current is produced even when the applied bias is much less than 0.3 V.

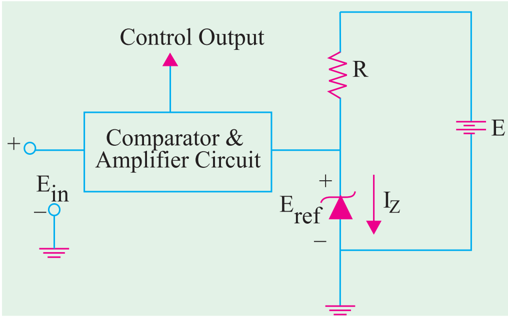


Fig. 54.15

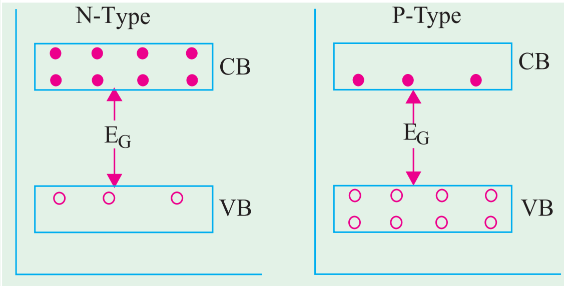


Fig. 54.16

This conduction mechanism in which charge carriers (possessing very little energy) bore through a barrier directly instead of climbing over it is called **tunneling.**

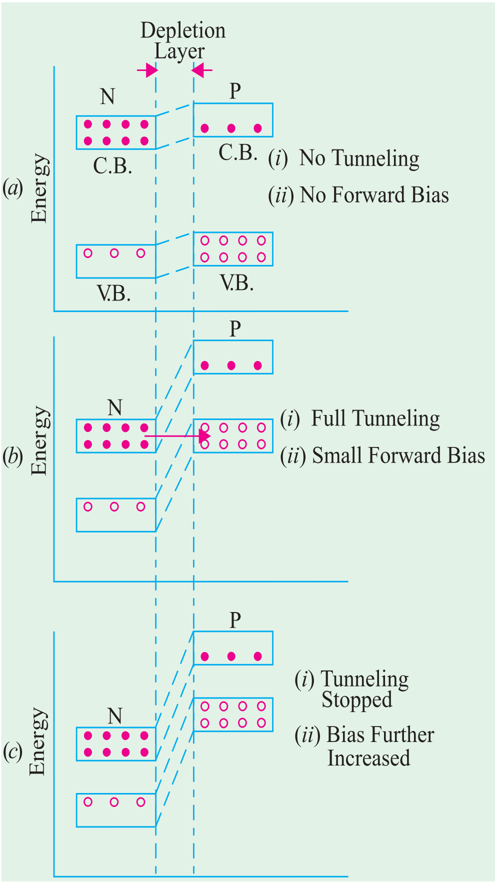


Fig. 54.17

Explanation

Energy band diagrams (EBD) of *N*-type and *P*-type semiconductor materials can be used to explain this tunneling phenomenon. Fig. 54.16 shows the energy band diagram of the two types of silicon separately. As explained earlier (Art. 51.21), in the *N*-type semiconductor, there is increased concentration of electrons in the conduction band. It would be further increased under heavy doping. Similarly, in a *P*-type material, there is increased concentration of holes in the valence band for similar reasons.

(*a*) No Forward Bias

When the *N*-type and *P*-type materials are joined, the EBD under no-bias conditiion becomes as shown in Fig. 54.17 (*a*). The junction barrier produces only a rough alignment of the two materials and their respective valence and conduction bands. As seen, the depletion region between the two is extremely narrow due to very heavy doping on both sides of the junction. The potential hill is also increased as shown.

* Much more than even for a Zener diode.

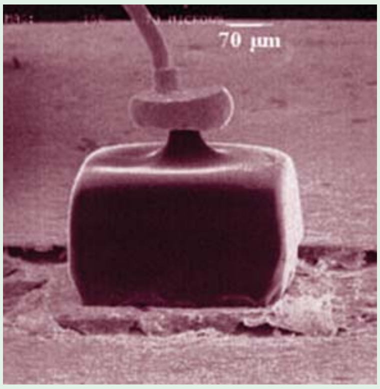
(b) Small Forward Bias

When a very small forward voltage (≅ 0.1 V) is applied, the EBDs become as shown in Fig. 54.17 (*b*). Due to the downward movement of the *N*-region, the *P*-region valence band becomes exactly aligned with the *N*-region conduction band. At this stage, electrons tunnel through the thin depletion layer with the velocity of light thereby giving rise to a large current called peak current I_p.

(c) Large Forward Bias

When the forward bias is increased further, the two bands get out of alignment as shown in Fig. 54.17 (*c*). Hence, tunneling of electrons stops thereby decreasing the current. Since current decreases with increase in applied voltage (*i.e.* dV/dI is negative), the junction is said to possess negative resistance at this stage. This resistance increases throughout the negative region.

However, it is found that when applied forward voltage is increased still further, the current starts increasing once again as in a normal junction diode.



Discrete commercial *Si* tunnel diode

54.7. Tunnel Diode

This diode was first introduced by Dr. Leo Easki in 1958.

(a) Construction

It is a high-conductivity two-terminal *P-N* junction diode having doping density about 1000 times higher as compared to an ordinary junction diode. This heavy doping produces following three unusual effects :

1. Firstly, it reduces the width of the depletion layer to an extremely small value (about 0.00001 mm).
2. Secondly, it reduces the reverse breakdown voltage to a very small value (approaching zero) with the result that the diode appears to be broken down for any reverse voltage.
3. Thirdly, it produces a negative resistance section on the *V/I* characteristic of the diode.

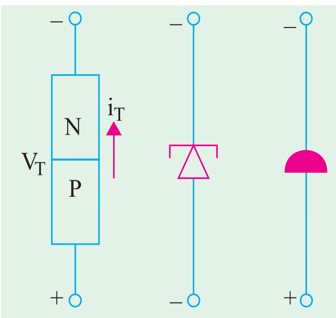


Fig. 54.18

It is called a ***tunnel*** diode because due to its extremely thin depletion layer, electrons are able to ***tunnel through*** the potential barrier at relatively low forward bias voltage (less than 0.05 V). Such diodes are usually fabricated from germanium, gallium-arsenide (GaAs) and gallium antimonide (GaSb).

The commonly-used schematic symbols for the diode are shown in Fig. 54.18. It should be handled with caution because being a low-power device, it can be easily damaged by heat and static electricity.

(b) V/I Characteristic

It is shown in Fig. 54.19. As seen, forward bias produces immediate conduction *i.e.* as soon as forward bias is applied, significant current is produced. The current quickly rises to its peak value I_p when the applied forward voltage reaches a value V_p (point *A*). When forward voltage is increased further, diode current starts decreasing till it achieves its minimum value called valley current I_v corresponding to valley voltage V_v (point *B*). For voltages greater than V_v, current starts increasing again as in any ordinary junction diode.

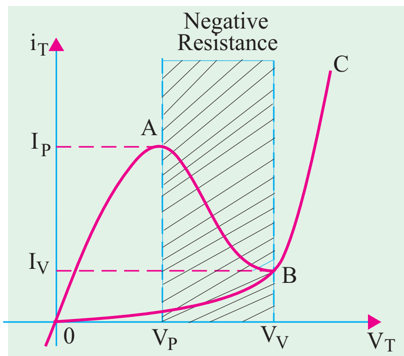


Fig. 54.19

As seen from Fig. 54.19, between the peak point *A* and valley point *B*, current decreases with increase in the applied voltage. In other words, tunnel diode possesses negative resistance (— R_N) in this region. In fact, this constitutes the most useful property of the diode. Instead of absorbing power, a negative resistance produces power. By offsetting losses in *L* and *C* components of a tank circuit, such a negative resistance permits oscillations. Hence, a tunnel diode is used as a very high frequency oscillator.

Another point worth noting is that this resistance increases as we go from point *A* to *B* because as voltage is increased, current keeps decreasing which means that diode negative resistance keeps increasing.

(*c*) Tunneling Theory

At zero forward bias, the energy levels of conduction electrons in *N*-region of the junction are slightly out of alignment with the energy levels of holes in the *P*-region. As the forward voltage is slightly increased, electron levels start getting aligned with the hole levels on the other side of junction thus permitting some electrons to cross over. This kind of junction crossing is called tunneling.

As voltage is increased to peak voltage (V_P), all conduction band electrons in the *N*-region are able to cross over to the valence band in the *P*-region because the two bands are exactly aligned. Hence, maximum current (called peak current I_P) flows in the circuit.

After V_P, as the applied voltage is increased, current starts decreasing because the two bands start gradually getting out of alignment. It reaches minimum value (called valley current) when the two are totally out of alignment at a forward bias of V_V (valley voltage).

For voltages greater than V_V, current starts increasing again exactly as it does in the case of an ordinary P-N junction diode.

Tunneling is much faster than normal crossing which enables a tunnel diode to switch ON and OFF much faster than an ordinary diode. That is why a tunnel diode is extensively used in special applications requiring very fast switching speeds like high-speed computer memories and high frequency oscillators etc.

(*d*) Diode Parameters

(*i*) Negative Resistance (– R_N). It is the resistance offered by the diode within the negative-resistance section of its characteristic (shown shaded in Fig. 54.19). It equals the reciprocal of the slope of the characteristic in this region.

It may also be found from the following relation $R_N = -\,dV/dI$.

Its value depends on the semiconductor material used (varying from – 10 Ω to – 200 Ω).

(*ii*) I_P/I_V Ratio

It is almost as important a factor (particularly for computer applications) as the negative resistance of the diode.

Silicon diodes have a low I_P/I_V ratio of 3 : 1 and their negative resistance can be approximated from $R_N = -\,200/I_P$. Such diodes are used mainly for switches operating in high ambient temperatures.

Germanium diodes have an I_P/I_V ratio of 6 : 1 and negative resistance formula $R_N = -\,120/I_P$. GaAs diodes (used exclusively in oscillators) have an I_P/I_V ratio of about 10 : 1 and a negative resistance nearly equal to that of silicon diodes.

The minimum I_P/I_V ratio for GaSb diode is about 12 : 1 and has the lowest resistance of all given by $R_N = -\,60/I_P$. Hence, such diodes have the lowest noise.

(*e*) Equivalent Circuit

The equivalent circuit of a tunnel diode is shown in Fig. 54.20. The capacitance *C* is the junction diffusion capacitance (1 to 10 pF) and (– R_N) is the negative resistance. The inductor L_S is due mainly to the terminal leads (0.1 to 4 nH). The resistance R_S is due to the leads, ohmic contact and semiconductor materials (1 – 5 Ω). These factors limit the frequency at which the diode may be used. They are also important in determining the switching-speed limit.

(*f*) Biasing the Diode

The tunnel diode has to be biased from some dc source for fixing its *Q*-point on its characteristic when used as an amplifier or as anoscillator and modulator.

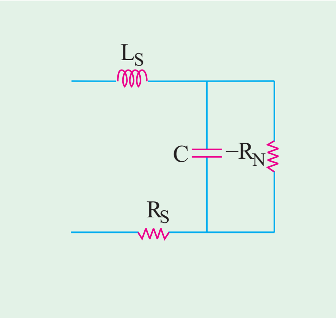


Fig. 54.20

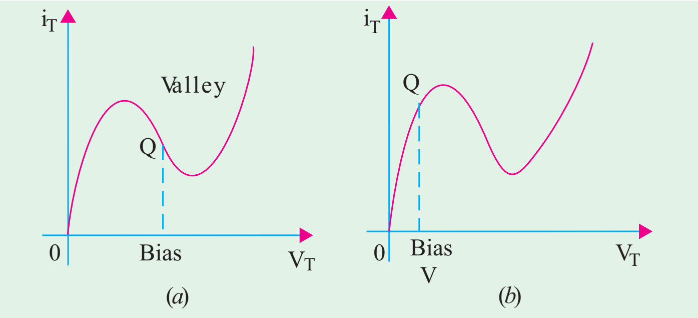


Fig. 54.21

The diode is usually biased in the negative region [Fig. 54.21 (*a*)]. In mixer and relaxation oscillator applications, it is biased in the positive-resistance region nearest zero [Fig. 54.21 (*b*)].

(*g*) Applications

Tunnel diode is commonly used for the following purposes :

1. as an ultrahigh-speed switch-due to tunneling mechanism which essentially takes place at the speed of light. It has a switching time of the order of nanoseconds or even picoseconds;

2. as logic memory storage device – due to triple-valued feature of its curve for current.

3. as microwave oscillator at a frequency of about 10 GHz – due to its extremely small capacitance and inductance and negative resistance.

4. in relaxation oscillator circuits – due to its negative resistance. In this respect, it is very similar to the unijunction transistor.

(*h*) Advantages and Disadvantages

The advantages of a tunnel diode are :

1. low noise, **2.** ease of operation, **3.** high speed,

4. low power, **5.** Insensitivity to nuclear radiations

The disadvantages are :

1. the voltage range over which it can be operated properly is 1 V or less;

2. being a two-terminal device, it provides no isolation between the input and output circuits.

54.8. Tunnel Diode Oscillator

The basic job of an oscillator is to convert dc power into ac power. Ordinarily, we do not expect an ac signal from a circuit which has no input ac source. But the circuit shown in Fig. 54.22 does exactly that as explained below.

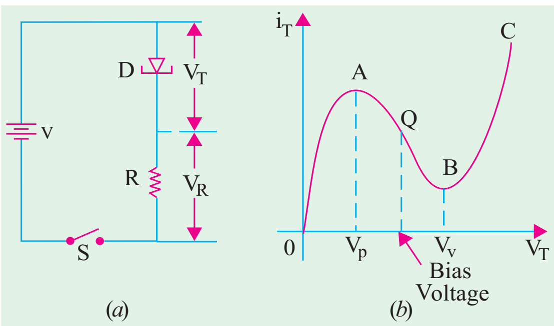


Fig. 54.22

The value of *R* is so selected as to bias the diode *D* in the negative-resistance region *A* –*B*. The working or quiescent point *Q* is almost at the centre of the curve *A* – *B*. When *S* is closed, the current immediately rises to a value determined by *R* and the diode resistance which are in series. The applied voltage *V* divides across *D* and *R* according to the ratio of their resistances.

However, as V_T exceeds V_P, diode is driven into the negative area and its resistance starts to increase (Art 4.7). Hence, V_T increases further till it becomes equal to valley voltage V_V (point *B*). At this point, further increase in V_T drives the diode into the positive- resistance region *BC* [Fig. 54.22

(*b*)]. The resulting increase in current now increases V_R but correspondingly decreases V_T, thereby bringing the diode back into the negative-resistance region. This decrease in V_T increases the circuit current till point *A* is reached when V_T equals V_P.

It describes one cycle of operation. In this way, the circuit will continue to oscillate back and forth through the negative-resistance region *i.e.* between points *A* and *B* on its characteristic. Its output across *R* is like a sine wave.

Fig. 54.23 shows a practical circuit drawn in two slightly different ways. Here, R_2 sets the proper bias level for the diode whereas R_1 (in parallel with the *LC* tank circuit) sets proper current level for it. The capacitor C_C is the coupling capacitor. As the switch *S* is closed, the diode is set into oscillations whose frequency equals the resonant frequency of the tank.

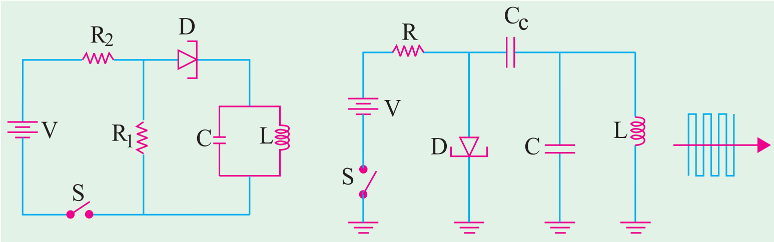


Fig. 54.23

54.9. Varactor Diode

The varactor diode is a semiconductor, voltage-dependent variable capacitor alternatively known as varicap or voltacap or voltage-variable capacitor (*VVC*) diode. Basically, it is just a reverse-biased junction diode whose mode of operation depends on its transition capacitance (C_T). As explained earlier in Art. 52.4, reverse-biased junctions behave like capacitors whose capacitance is $\propto 1/V_R^n$ where *n* varies from 1/3 to 1/2. As reverse voltage V_R is increased, depletion layer widens thereby decreasing the junction capacitance. Hence, we can change diode capacitance by simply changing V_R. Silicon diodes which are optimised for this variable capacitance effect are called varactors.

The picture, schematic symbol and a simple equivalent circuit for a varactor are shown in Fig. 54.24.

Varactor diode

Varactors may be of two types as shown in Fig. 54.25. The doping profile of the abrupt-junction diode is shown in Fig. 54.25 (*a*) and that of the hyperabrupt-junction diode in Fig. 54.25 (*b*). The abrupt-junction diode has uniform doping and a capacitive tuning ratio (*TR*) of 4 : 1. For example, if its maximum transition capacitance is 100 pF and minimum 25 pF, then its *TR* is 4 : 1 which is not enough to tune a broadcast receiver over its entire frequency range of 550 to 1050 kHz.

The hyperabrupt-junction diode has highest impurity concentration near the junction. It results in narrower depletion layer and larger capacitance. Also, changes in V_R produce larger capacitance changes. Such a diode has a tuning range of 10 : 1 enough to tune a broadcast receiver through its frequency range of nearly 3 : 1.

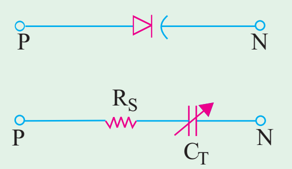


Fig. 54.24

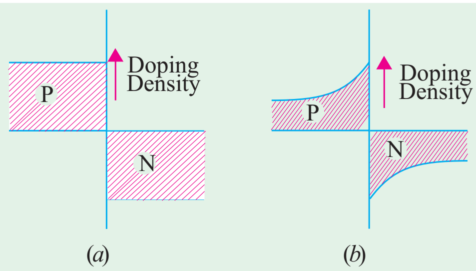


Fig. 54.25

Applications

Since the junction capacitance of a varactor is in the pF range, it is suitable for use in high-frequency circuits. Its main applications are as

1. automatic frequency control device, **2.** FM modulator,
3. adjustable band-pass filter, **4.** Parametric amplifier.

54.10. PIN Diode

(*a*) Construction

It is composed of three sections. These are the usual *P* and *N*-regions but sandwiched between them is an intrinsic layer or *I*-layer of pure silicon (Fig. 54.26). Being intrinsic (or undoped) layer, it offers relatively high resistance. This high-resistance region gives it two advantages as compared to an ordinary *P-N* diode. The advantages are :

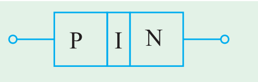


Fig. 54.26

Pin diode

1. decrease in capacitance C_{pn} because capacitance is inversely proportional to the seperation of *P*-and *N*-regions. It allows the diode a faster response time. Hence, PIN diodes are used at high frequencies (more than 300 MHz);

2. possibility of greater electric field between the *P*-and *N*-junctions. It enhances the electron-hole pair generation thereby enabling PIN diode to process even very weak input signals.

(*b*) Diode Resistance

1. When forward-biased, it offers a variable resitance $r_{ac} \cong 50/I$ where *I* is the dc current in mA (Art. 52.2). For large dc currents, it would look like a *short*.

2. When reverse-biased, it looks like an 'open' *i.e.* it offers infinite resistance in the reverse direction.

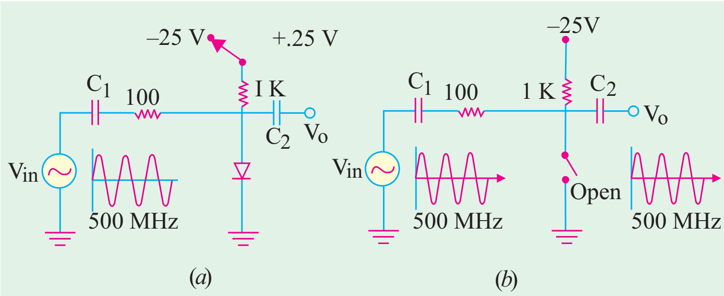


Fig. 54.27

(*c*) Operation

(*i*) **High Frequency Switching.** Its use in electronic high frequency switching is illustrated in Fig. 54.27.

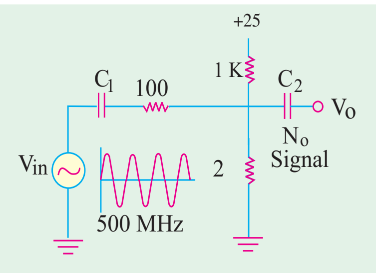


Fig. 54.28

When the diode is reverse-biased, it looks like an 'open' as shown in Fig. 54.27 (*b*). The 500-MHz input signal voltage divides across the series-connected 100 Ω resistance and the diode in proportion to their resistances. Since the diode has infinite resistance (being open), the entire input signal appears across it. Hence, the whole input signal passes out *via* coupling capacitor C_2 without any attenuation (or loss). When the diode is forward-biased by the + 25 V dc source, $I = 25/1\ K = 25$ mA. Hence, diode resistance $r_{ac} = 50/25 = 2\ \Omega$ as shown by its equivalent circuit in Fig. 54.28. Now, almost all the input signal voltage drops across 100 Ω resistance and practically none across the 2 Ω resistance. Hence, there is hardly any signal output.

In practice instead of mechanically switching the diode-biasing supply from – 25 V to + 25 V, a transistor is used to do this switching operation. In this way, we can turn a very high frequency signal (MHz range) OFF and ON with the speed of a transistor switching circuit.

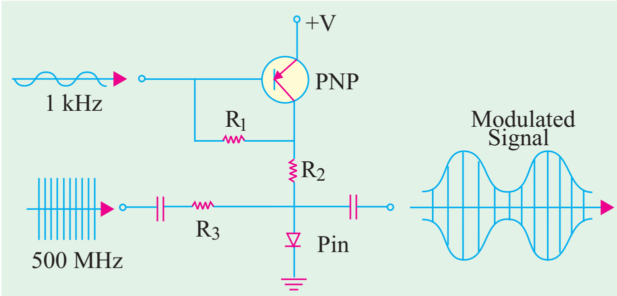


Fig. 54.29

***(ii)* Use as AM Modulator.** The way in which the 500-MHz signal is modulated at 1 kHz rate is illustrated in Fig. 54.29.

A 1 kHz signal is fed into a *PNP* transistor where it varies its dc output current at the same rate. This varying dc current is applied as biasing current to the PIN diode as shown in Fig. 54.29. It varies the diode ac resistance as seen by the 500 MHz signal. Hence, the signal is modulated at 1 kHz rate as shown.

(*d*) Applications

(*i*) as a switching diode for signal frequencies upto GHz range;

(*ii*) as an AM modulator of very high frequency signals.

54.11. Schottky Diode

It is also called Schottky barrier diode or ***hot-carrier*** diode. It is mainly used as a rectifier at signal frequencies exceeding 300 MHz. It has more uniform junction region and is more rugged than PIN diode – its main rival.

Schottky barrier diode family expands to meet needs of power related application

(*a*) Construction

It is a metal-semiconductor junction diode with ***no depletion layer***. It uses a metal (like gold, silver, platinum, tungsten etc.) on the side of the junction and usually an *N*-type doped silicon semiconductor on the other side. The diode and its schematic symbol are shown in Fig. 54.30.

(*b*) Operation

When the diode is unbiased, electrons on the *N*-side have lower energy levels than electrons in the metal. Hence, they cannot surmount the junction barrier (called Schottky barrier) for going over to the metal.

When the diode is forward-biased, conduction electrons on *N*-side gain enough energy to cross the junction and enter the metal. Since these electrons plunge into the metal with very large energy, they are commonly called ***'hot-carriers'***. That is why this diode is often referred to as hot-carrier diode.

(*c*) Applications

This diode possesses two unique features as compared to an ordinary *P-N* junction diode :

1. it is a unipolar device because it has electrons as majority carriers on both sides of the junction. An ordianry *P-N* junction diode is a bipolar device because it has both electrons and holes as majority carriers;
2. since no holes are available in metal, there is ***no depletion layer or stored charges*** to worry about. Hence, Schottky diode can switch OFF faster than a bipolar diode.

Because of these qualities, Schottky diode can easily rectify signals of frequencies exceeding 300 MHz. As shown in Fig. 54.31, it can produce an almost perfect half-wave rectified output.

The present maximum current rating of the device is about 100 A. It is commonly used in switching power supplies that operate at frequencies of 20 GHz. Another big advantage of this diode is its low noise figure which is extremely important in communication receivers and radar units etc.

It is also used in clipping and clamping circuits, computer gating, mixing and detecting networks used is communication systems.

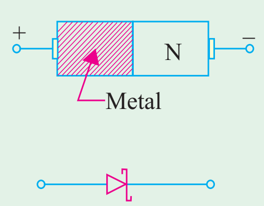


Fig. 54.30

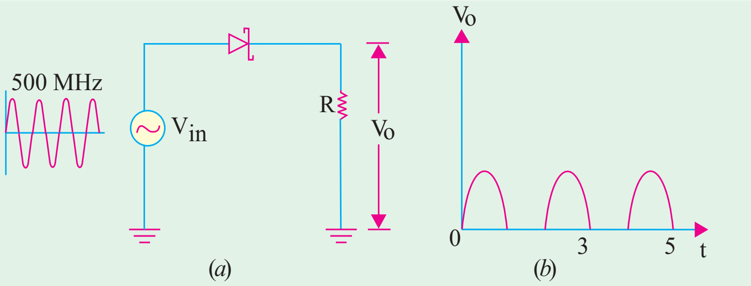


Fig. 54.31

54.12. Step Recovery Diode

It is another type of VVC diode having a ***graded doping profile*** where doping density decreases near the junction as shown in Fig. 54.32. This results in the production of strong electric fields on both sides of the junction.

(*a*) Theory

At low frequencies, an ordinary diode acts as a rectifier. It conducts in the forward direction but not in the reverse direction *i.e.* it recovers immediately from ON state to the OFF state. However, it is found that when driven forward-to-reverse by a high-frequency signal (above a few MHz), the diode does not recover immediately. Even during the negative half-cycle of the input signal when the diode is reverse-biased, it keeps conducting for a while after which the reverse current ceases abruptly in one step. This reverse conduction is due to the fact that charges stored in the depletion layer during the period of forward bias take time to drain away from the junction.

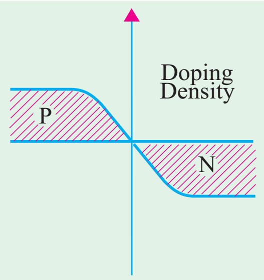


Fig. 54.32

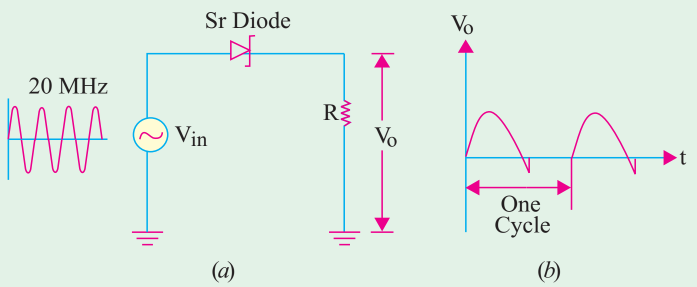


Fig. 54.33

Fig. 54.33 (*a*) shows a step-recovery diode being driven by a 20-MHz signal source. As seen from Fig. 54.33 (*b*), it conducts in the forward direction like any diode. During the reverse half-cycle, we get reverse current due to the draining of the stored charge after which current suddenly drops to zero. It looks as though diode has suddenly ***snapped open*** during the early part of the reverse cycle. That is why it is sometimes called a ***snap diode.***

The step or sudden recovery from reverse current ON to reverse current OFF gives the diode its name.

(*b*) Applications

Its main use is in high-frequency harmonic generator circuits as a frequency multiplier as explained below.

It is found that whenever a waveform has sudden step or transition, it contains all the harmonics of the input signal (*i.e.* multiples of its fundamental frequency). For example, the output waveform of Fig. 54.33 (*b*) contains waves of frequencies 40 MHz, 60 MHz, 80 MHz and so on.

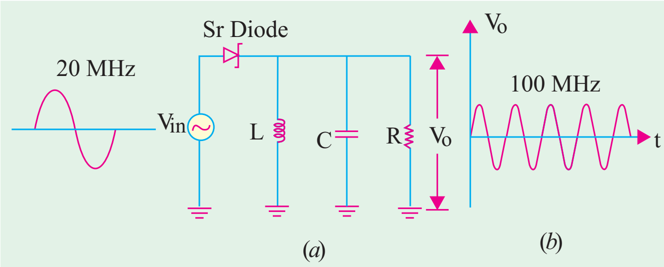


Fig. 54.34

Fig. 54.34 shows how the output of a step recovery diode can be used to drive a tuning circuit which can be made to tune out all harmonics except one *i.e.* fifth in this case (100 MHz). With an input signal of 20 MHz, the step recovery diode generates harmonics of different multiple frequencies listed above. However, the resonant *L*-*C* circuit is tuned to 5th harmonic of f = 100 MHz. Hence, all except this harmonic are filtered out of the circuit. The signal appearing across R is almost a pure sine wave with f = 100 MHz as shown separately in Fig. 54.34 (*b*).

Step-recovery diodes are also used in pulse and digital circuits for generating very fast pulses with rise time of less than 1 nanosecond.

54.13. Gunn Diode

It is a negative-resistance microwave device for oscillator applications.

As shown in Fig. 54.35, it consists of a thin slice of *N*-type gallium arsenide sandwiched between two metal conductors. The central section is *N*-gallium arsenide whereas the two outer sections are epitaxially grown from GaAs with increased doping and higher conductivity. As an oscillator, its frequencies range from 5 GHz and 100 mW output upto 35 GHz and 1 mW output. Efficiencies of 3 to 5 per cent are possible at present. Fig. 54.35(*b*) shows the picture of a Gunn diode.

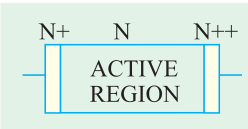


Fig. 54.35(*a*)

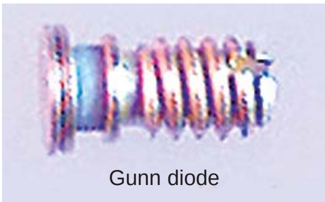


Fig. 54.35(*b*)

54.14. IMPATT Diode

IMPATT stands for ***impact avalanche and transit time*** diode. As the name indicates, it is a microwave diode that utilizes the delay time required for attaining an avalanche condition plus transit time to produce a negative-resistance characteristic. It is used as a microwave oscillator within a frequency range of 10-100 GHz.

Tutorial Problems 54.1

1. Is the ideal Zener diode shown in Fig. 54.36 properly biased ? If not, explain why ? **[No]**
2. Check up if the diode in Fig. 54.37 is biased properly for normal operation. What is the current taken by the diode ? **[Yes : 4 mA]**
3. Check up if Zener diode of Fig. 54.38 is reverse-biased as well as properly voltage-biased. Calculate diode current and power dissipation. **[6 mA, 96 mW]**
4. Using ideal Zener diode approximations, find the minimum and maximum currents through the diode in Fig. 54.39. **[4 mA, 8 mA]**

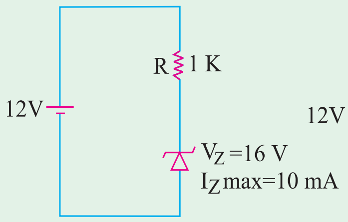


Fig. 54.36

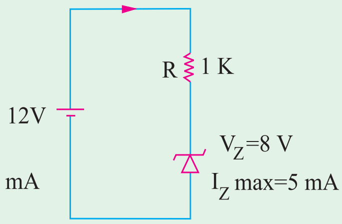


Fig. 54.37

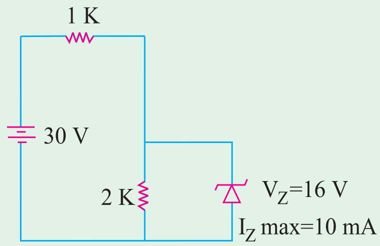


Fig. 54.38

5. A 9 V stabilized voltage supply is required to run a car stereo system from car's 12 V battery. A Zener diode with V_z = 9 V and P_{max} = 0.25 W is used as a voltage regulator as shown in Fig. 54.40.

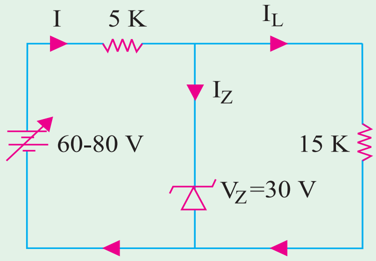


Fig. 54.39

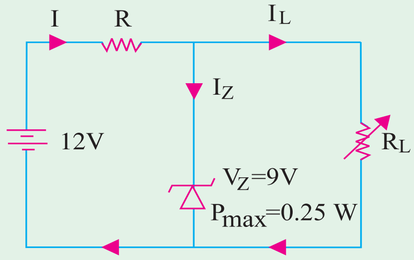


Fig. 54.40

Find the value of the series resistor *R*. **[120 Ω]**

6. A load of 1kW is connected across a 10 V Zener regulator as shown in Fig. 54. 41. The zener current can vary between 5mA to 55mA while maintaining the voltage constant. Find the minimum and maximum voltage level at input.

(Electronic Devices and Circuits, Nagpur Univ. Summer, 2004)

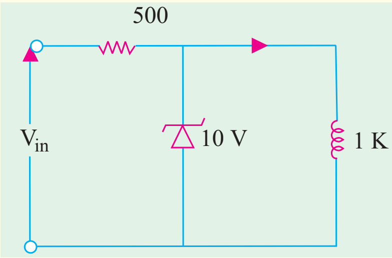


Fig. 54.41

7. A 24V, 600 mW zener diode is used for providing a 24V stabilized supply to a variable load. If the input voltage is 32V, calculate
   (*i*) the value of series resistance required.
   (*ii*) diode current when the load is 1200 Ω

(Electronics Engg., Bangalore Univ. 2003)

OBJECTIVE TESTS – 54

1. Silicon is preferred for manufacturing Zener diodes because it
   (*a*) is relatively cheap
   (*b*) needs lower doping level
   (*c*) has higher temperature and current capacity
   (*d*) has lower break-down voltage.
2. When used in a circuit, a Zener diode is always
   (*a*) forward-biased
   (*b*) connected in series
   (*c*) troubled by overheating
   (*d*) reverse-biased.
3. The main reason why electrons can tunnel through a *P-N* junction is that
   (*a*) they have high energy
   (*b*) barrier potential is very low
   (*c*) depletion layer is extremely thin
   (*d*) impurity level is low.
4. The I_P/I_V ratio of a tunnel diode is of primary importance in

(*a*) determining tunneling speed of electrons
(*b*) the design of an oscillator
(*c*) amplifier designing
(*d*) computer applications.

5. Mark the INCORRECT statement. A varactor diode
(*a*) has variable capacitance
(*b*) utilizes transition capacitance of a junction
(*c*) has always a uniform doping profile
(*d*) is often used as an automatic frequency control device.

6. The microwave device used as an oscillator within the frequency range 10-1000 GHz is .... diode.
(*a*) Schottky
(*b*) IMPATT
(*c*) Gunn
(*d*) Step Recovery.

7. A PIN diode is frequently used as a
(*a*) peak clipper
(*b*) voltage regulator
(*c*) harmonic generator
(*d*) switching diode for frequencies upto GHz range.

8. Mark the WRONG statement. A Schottky diode
(*a*) has no depletion layer
(*b*) has metal-semiconductor junction
(*c*) has fast recovery time
(*d*) is a bipolar device
(*e*) is also called hot-carrier diode
(*f*) can easily rectify high-frequency signals.

9. A special purpose diode which uses metals like gold, silver or platinum on one side of the junction, *n*-type doped silicon on another side and has almost no charge storage in the junction, is a
(*a*) Schotty diode
(*b*) tunnel diode
(*c*) varactor diode
(*d*) zener diode

10. A step-recovery diode
(*a*) has an extremely short recovery time
(*b*) conducts equally well in both directions
(*c*) is mainly used a harmonic generator
(*d*) is an ideal rectifier of high-frequency signals.

11. A semiconductor device that resembles a voltage variable capacitor is called diode.
(*a*) tunnel
(*b*) PIN
(*c*) Schottky
(*d*) varactor

12. A diode that has no depletion layers and operates with hot carriers is called ...... diode.
(*a*) Schottky
(*b*) Gunn
(*c*) step recovery
(*d*) PIN

13. In switching devices, gold doping is used to
(*a*) improve bonding
(*b*) reduce storage time
(*c*) increase the mobility of the carrier
(*d*) protect the terminals against corrosion

14. When the reverse bias voltage of a varactor diode increases, its
(*a*) capacitance decreases
(*b*) lealkage current decreases
(*c*) negative resistance increases
(*d*) depletion zone decreases.

15. Which of the following are negative-resistance microwave diodes oscillator applications ?
(*a*) Gunn
(*b*) IMPATT
(*c*) step recovery
(*d*) both (*a*) and (*b*)
(*e*) both (*b*) and (*c*).

16. A negative-resistance microwave diode having a thin slice of a semiconductor material sandwiched between two metal conductors is called .... diode.
(*a*) Schottky
(*b*) PIN
(*c*) Gunn
(*d*) varactor.

17. Zener diodes are used primarily as
(*a*) rectifiers
(*b*) voltage regulators
(*c*) oscillators
(*d*) amplifiers.

18. The diode which is often used for voltage regulation in electronic circuits is called ...... diode

(*a*) zener (*b*) varactor

(*c*) silicon (*d*) germanium.

19. Avalanche photodiodes are preferred over PIN diodes in optical communication systems because of

(*a*) speed of operation

(*b*) higher sensitivity

(*c*) larger bandwidth

(*d*) larger power handling capacity

20. The current through the Zener diode in Fig. 54. 42.

(*a*) 33 mA

(*b*) 3.3 mA

(*c*) 2 mA

(*d*) 0 mA

(GATE ; 2004)

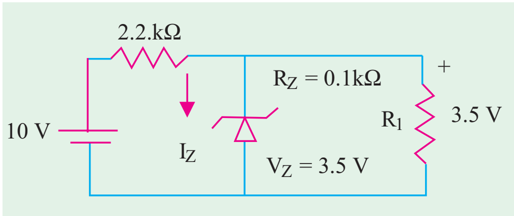


Fig. 54.42

ANSWERS

1.	(*c*)	**2.**	(*d*)	**3.**	(*c*)	**4.**	(*d*)	**5.**	(*c*)	**6.**	(*b*)	**7.**	(*d*)	**8.**	(*d*)	**9.**	(*a*)	**10.**	(*c*)
11.	(*d*)	**12.**	(*a*)	**13.**	(*b*)	**14.**	(*a*)	**15.**	(*d*)	**16.**	(*b*)	**17.**	(*b*)	**18.**	(*a*)	**19.**	(*a*)	**20.**	(*c*)

GO To FIRST