Unit - II Microwave Diodes and Diode Circuits.

Diode

→ A diode is a specialized electronic component with two electrodes called the anode and the cathode. Most diodes are made with semiconductor materials such as silicon, germanium, or selenium. Some diodes are comprised of metal electrodes in a chamber evacuated or filled with a pure elemental gas at low pressure. Diodes can be used as rectifiers, switches, signal modulators, signal mixers, signal demodulators, and oscillators.

The fundamental property of a diode is its tendency to conduct electric current in only one direction. When the cathode is negatively charged relative to the anode at a voltage greater than a certain minimum called forward breakover, then current flows through the diode.

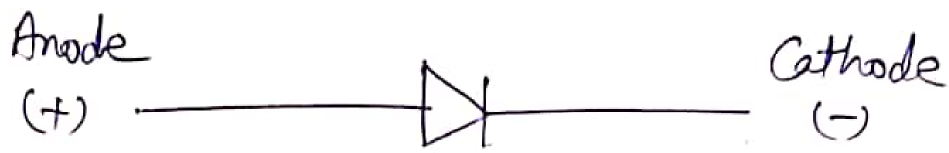
Silicon → 0.6 V
germanium → 0.3 V
selenium → 1 V

If the cathode is positive with respect to the anode, or is negative by an amount less than the forward breakover voltage, then the diode does not conduct current. This is a simplistic view, but is true for diodes operating as rectifiers, switches, and limiters.

forward breakover voltage is approximately (2)
six tenth of a volt (0.6 V) for silicon devices (Si)14, 0.3 V for germanium (Ge)32 devices, and 1V for selenium (Se)34 devices.

⇒ A diode is a device which only allows unidirectional flow of current if operated within a rated specified voltage level.

Symbol of Diode:-

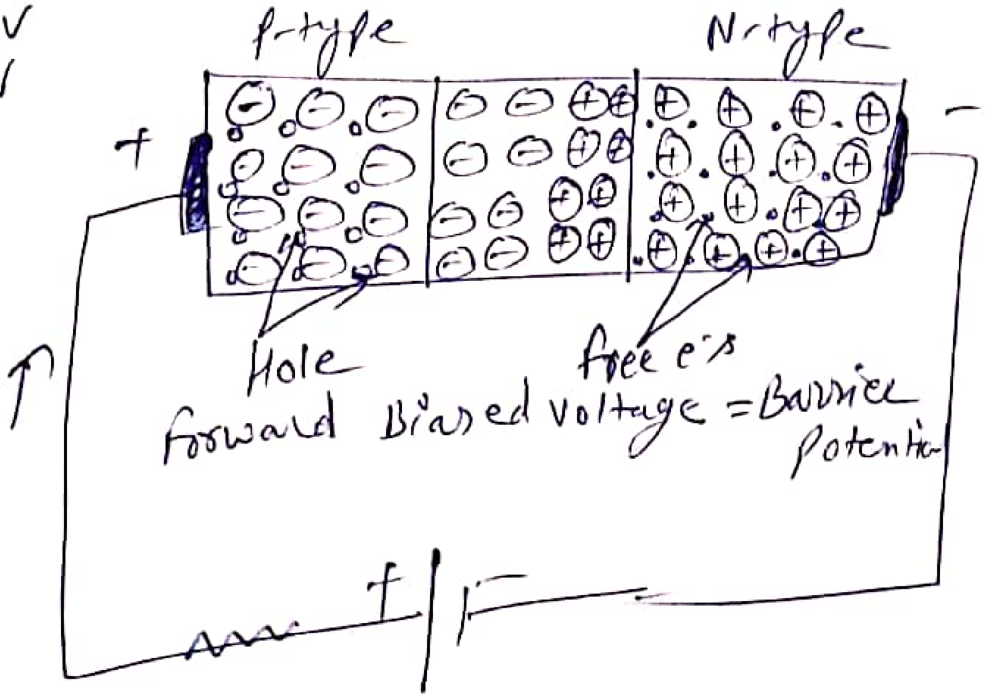


→ A simple PN junction diode can be created by doping donor impurity in one portion and acceptor impurity in other portion of a silicon or germanium crystal block. These make a p n junction at the middle portion of the block beside which one portion is p-type (which is doped by trivalent or acceptor impurity) and other portion is n type (which is doped by pentavalent or donor impurity). It can also be formed by ~~joing~~ joining a P-type (intrinsic semiconductor doped with a trivalent impurity) and n-type semiconductor (intrinsic semiconductor doped with a pentavalent impurity) together with a special fabrication technique such that a p-n junction is formed.

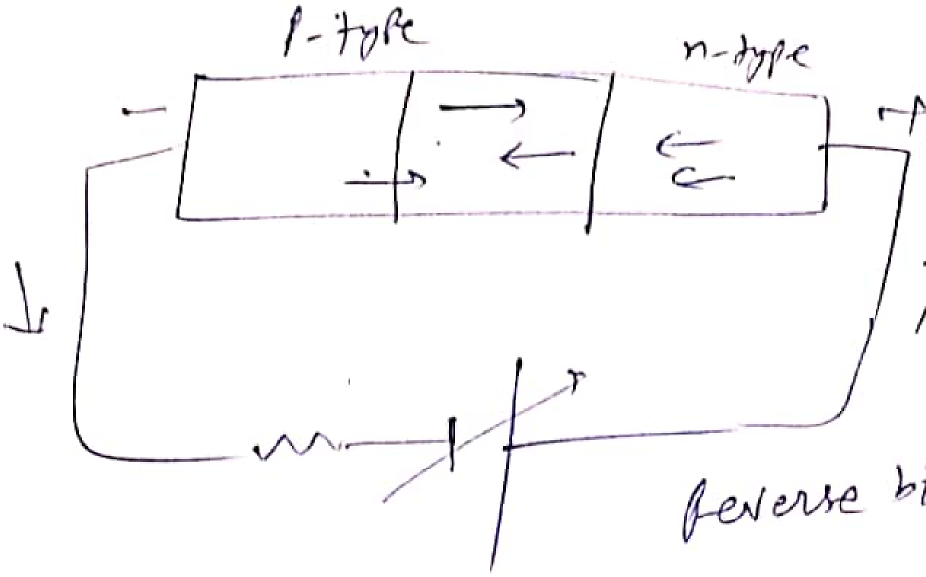
→ Working Principle of Diode:-

→ The n-side will have a large number of e⁻'s and very few holes (due to thermal excitation) whereas the p-side will have a high concentration of holes and very few electrons. Due to this, a process called diffusion takes place. In this process free e⁻'s from the n-side will diffuse (spread) into the p-side and combine with holes present there, leaving a positive immobile (not moveable) ion in the n-side. Hence, few atoms on the p-side are converted into negative ions. Similarly, few atoms on the n-side will get converted to positive ions. Due to this large number of positive ions and negative ions will accumulate on the n-side and p-side respectively. This region so formed is called as depletion region. Due to the presence of these positive and negative ions a static electric field called as "barrier potential" is created across the p-n junction of the diode. It is called as "barrier potential" because it acts as a barrier and opposes the further migration of holes and e⁻'s across the junction.

Si → 0.7V
Ge → 0.3V



Forward Biased voltage = Barrier Potential



(1) PIN Diode :-

PIN → p-type, Intrinsic, n-type

→ In a PIN (p- intrinsic - n) diode, the semiconductor wafer has a heavily doped narrow layer of p-type material seperated from an equally heavily doped narrow layer of n-type material by a thicker layer of high resistivity material that is intrinsic (or very lightly doped material) as shown in fig.

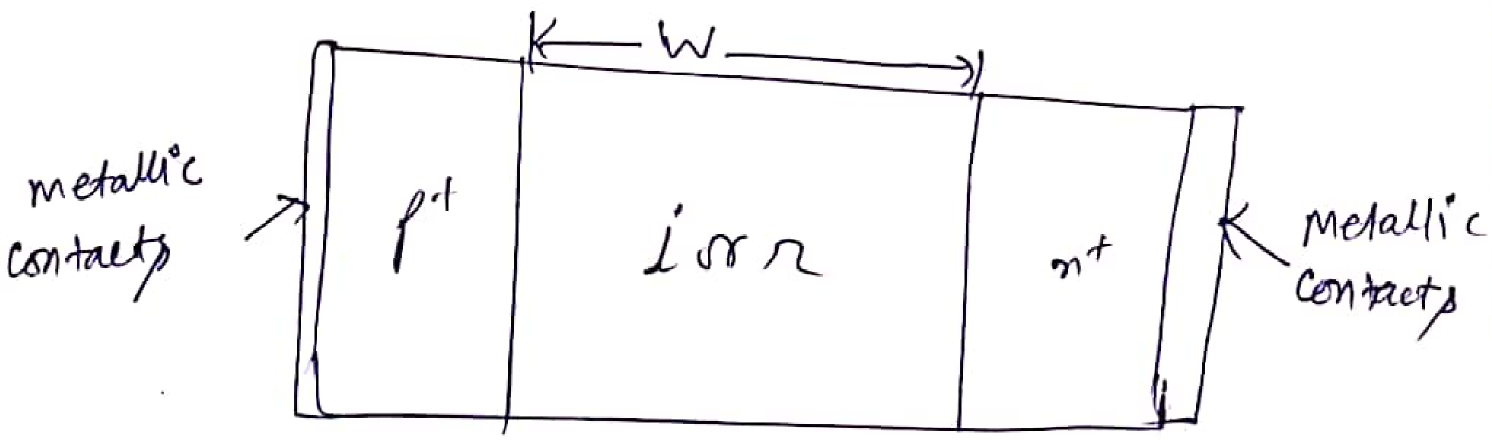
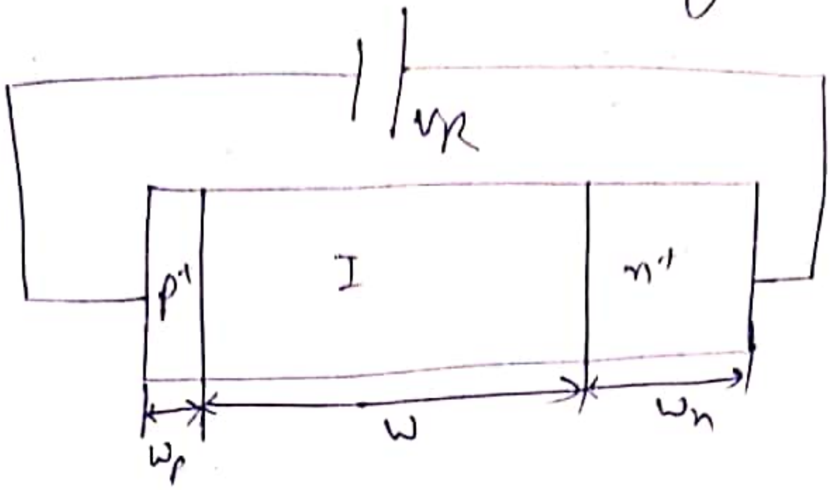


fig → structure of PIN Diode

→ PIN diode consists of heavily doped P and N regions separated by a wide intrinsic region.



→ Intrinsic region offers the high resistance to the current through it.

→ The wide intrinsic region makes the PIN diode an inferior rectifier (one typical function of a diode but it makes the PIN diode suitable for attenuators, fast switches, photo detectors, and high voltage power electronics applications.

→ PIN diode works as an ordinary PN junction diode frequencies up to a 100 MHz.

→ Above 100MHz it sizes its operation of rectifier and behaves as a switches or resistance.

→ In reverse bias it acts as a capacitor.

→ BIASING OF PIN DIODE :-

1.) UNBIASED :- When the PIN is unbiased there is a diffusion of e⁻ across the junction. Depletion region is formed between PI and IN regions with more penetration in intrinsic region.

(2) **Forward bias:-** When the diode is forward biased the injected carrier concentration is typically several orders of magnitude higher then the intrinsic level carrier concentration.

→ Due to this high level injection, which in turn is due to the depletion region, the electric field extends deeply into the region.

→ This electric field helps in speeding up of the transport of charge carriers from P to N region which results in faster operation of the diode, making it a suitable device for high frequencies operations.

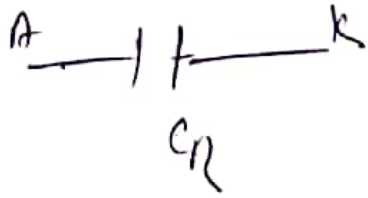
→ In forward bias the diode behaves as a variable resistance and resistance decreases with increase in forward bias voltage.

Variable resistor in forward bias

(3) **Reverse Bias:-** As the reverse bias voltage is increased the depletion layer thickness increases. The device behaves as a variable capacitor until the intrinsic region becomes free of mobile carriers.

→ This voltage is called swept out voltage.

→ At this voltage the device works as a ~~capac~~ constant capacitor.



Applications :-

- Rf and dc controlled microwave switches.
- Rf and variable attenuator.
- In limiter circuit.
- Photo detector and photo voltaic cell.
- Rf modulator circuits.

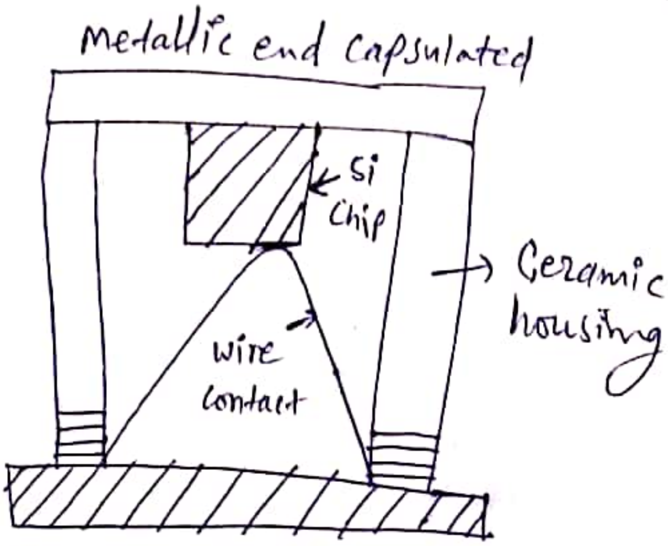


Fig. 1 Construction of PIN diode

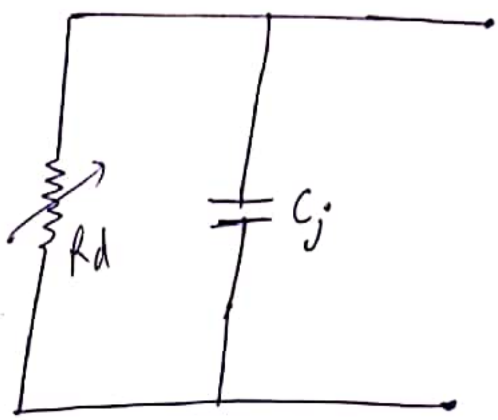
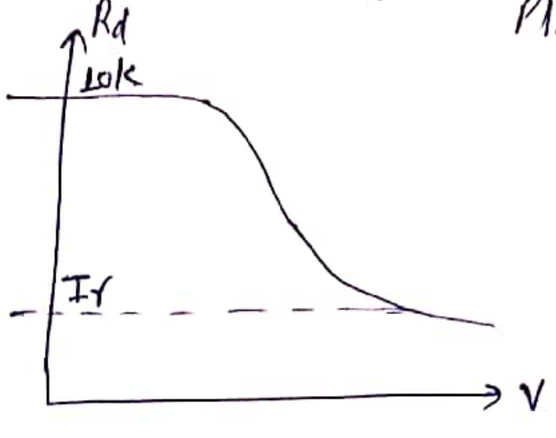


fig. 2 Equivalent circuit of PIN diode



Resistance variation with bias.

- Although gallium arsenide (GaAs) can be used in the construction of PIN diode but silicon tends to be the main material, because of its high power handling capacity and resisdivity and at the same time ease of fabrication. PIN diodes are widely used for microwave power switching, limiting and modulation.

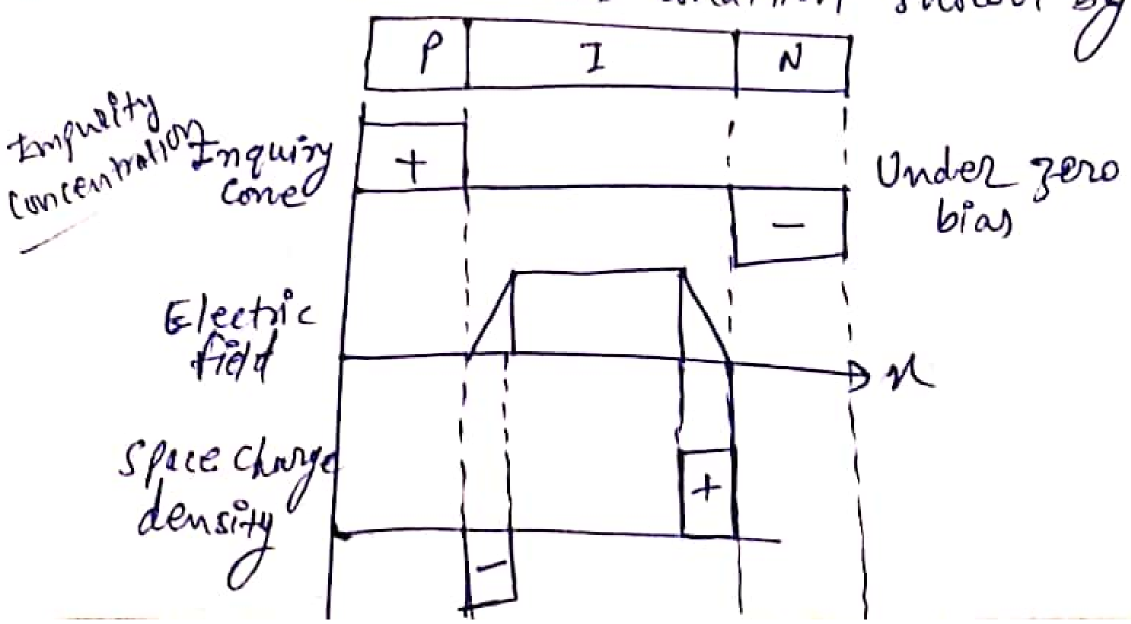
→ The PIN diode acts as a low frequency rectifier that could rectify more power than an ordinary p-n junction diode up to 100 MHz, the operation is similar to an ordinary p-n junction diode. At higher frequencies the PIN diode acts like a variable resistance.

→ Rectification ceases at higher frequencies due to the carrier storage junction and the transit time across the large intrinsic region.

→ Now, basic principle of operation of the diode is the variation of resistance by varying the biasing voltage as mentioned. Under reverse biased condition resistance changes from 5 to 10KΩ and under forward bias condition the resistance varies between 1 and 10Ω. Thus, when the diode is mounted across a co-axial or a waveguide, by varying the reverse biasing voltage the diode impedance can be matched with the impedance of the transmission line and as a result maximum power can be transmitted. Whereas, under forward bias condition the diode offers a very low impedance (nearly equal to zero) across the waveguide and as a result most of the power will be reflected back and hardly any is transmitted.

→ Operation of PIN Diode :-

The operation can be explained by considering zero bias, reverse and forward bias condition shown by fig.



1. Zero bias:- At zero bias the diffusion of the holes and e⁻s across the junction causes space charge (density) region of thickness inversely proportional to the impurity concentration. An ideal 'i' layer has no depletion region i.e. p layer has a fixed negative charge and n layer has a fixed positive charge under zero bias.

2. Reverse bias:- As reverse bias is applied, the space charge regions in the p and n layers will become thicker. The reverse resistance will be very high and almost constant.

3. Forward bias:- With forward bias carriers will be injected into the i layer and the p and n space charge regions will become thinner i.e., e⁻s and holes are injected into the 'i' layer from p and n layers respectively. This results in the carrier concentration in the 'i' layer becoming raised above equilibrium levels and the resistivity drops as forward bias is increased. Thus low resistance is offered in the forward direction.

⇒ Applications of PIN diode:-

(i) PIN diode as a switch:- It can be used either in series or in shunt. In the first case when the diode is reverse biased, switch is 'off' or open and when it is forward biased it is closed. The bias is changed by a suitable control system as shown in fig.

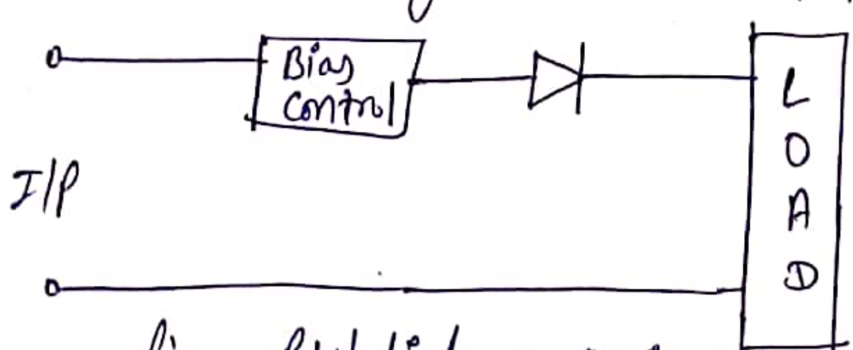


fig:- PIN diode as series switch.

In the second case when the diode is forward biased, it offers a short circuit. Hence energy is fully reflected back and no power flows to the load. Hence switch is open. If reverse biased the diode is open, hence the load receives the power i.e. switch is closed as shown in fig..

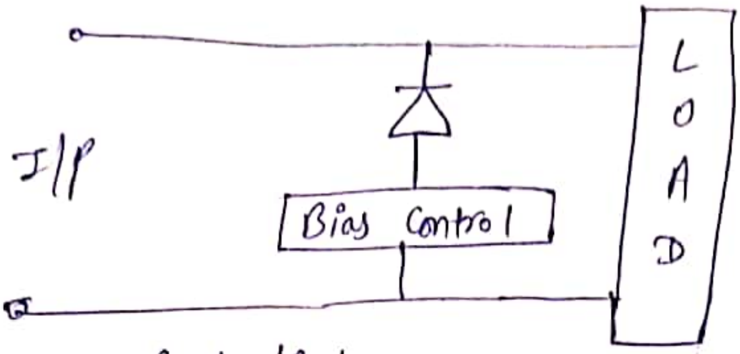


fig → PIN diode as shunt switch.

(ii) PIN diode as amplitude Modulator:- The diode is kept at low reverse bias and in series with the low frequency modulating signal. The modulating signal amplitude is kept smaller then the RF carrier signal. The modulating signal changes the RF resistance of diode so the varying amount of mismatch result. Hence the amount of carrier power reflected back and hence the amount of carrier passed beyond diode circuit towards the output varies as the input value of modulating signal.

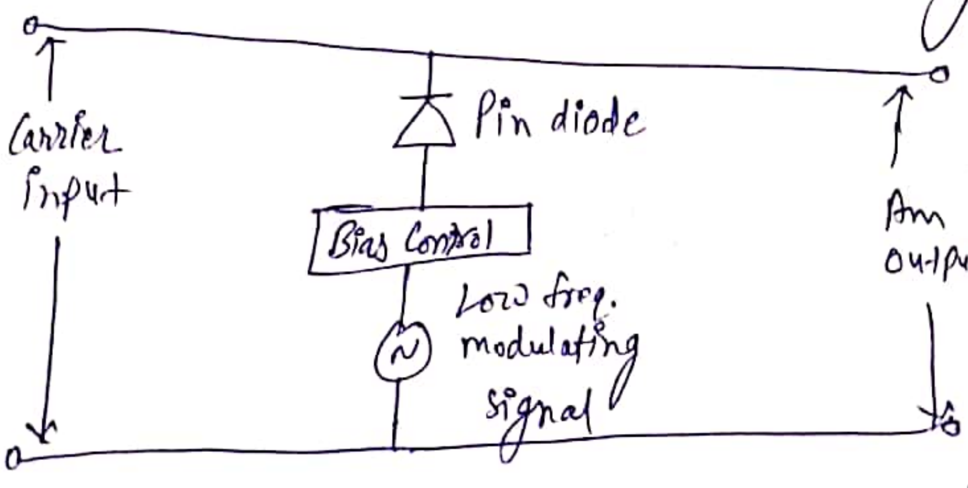


fig:- Amplitude modulator using PIN diode

(iii) PIN diode as phase shifter:- The circular coupled phase shifter is shown in fig. Here S represents a PIN diode switch. The input signal travels a distance equal to L or L+l depending on whether S is closed or open respectively. (11)

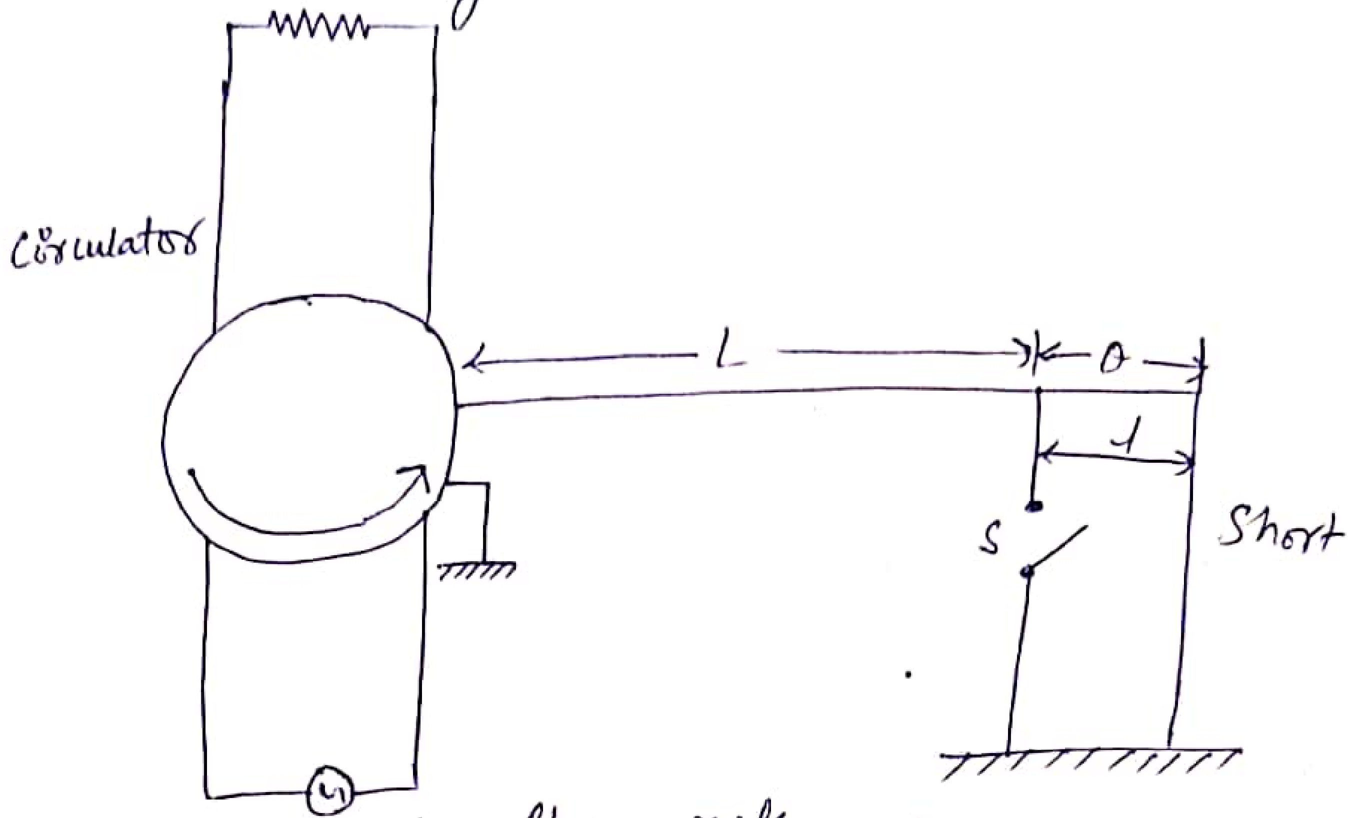


fig:- Phase shifter using PIN diode.

Therefore between the two conditions we have a phase shift of 2θ (the signal has to travel to permanent short and return). By adjusting 'l' phase shift can be adjusted. "L" will be far greater in magnitude then "l" which will be fraction of a wavelength. It finds application in phased array radars.

→ Varactor Diode :-

The term varactor comes from the word variable reactor and means a device whose reactances can be varied in a controlled manner with a bias voltage, as shown in fig.

Basically it is a p-n junction diode whose junction capacitance is a function of the applied voltage, hence can be used as non-linear device. In a p-n junction diode when it is reversed bias the majority carriers from both p and n-side will move away from the junctions and forms a charge free region called depletion region across the junction and gives rise to a junction capacitance. The width of the depletion layer varies with biasing voltage, hence the junction capacitance. Varactor is p^+n-n^+ or n^+p-p^+ type of diode.

The junction capacitance depends on the applied voltage and junction design also. In some cases a junction with fixed reverse bias may be used as a capacitance of a fixed value. The V-I characteristics of a typical varactor diode is shown in fig. Commonly used schematic symbols are shown in fig.

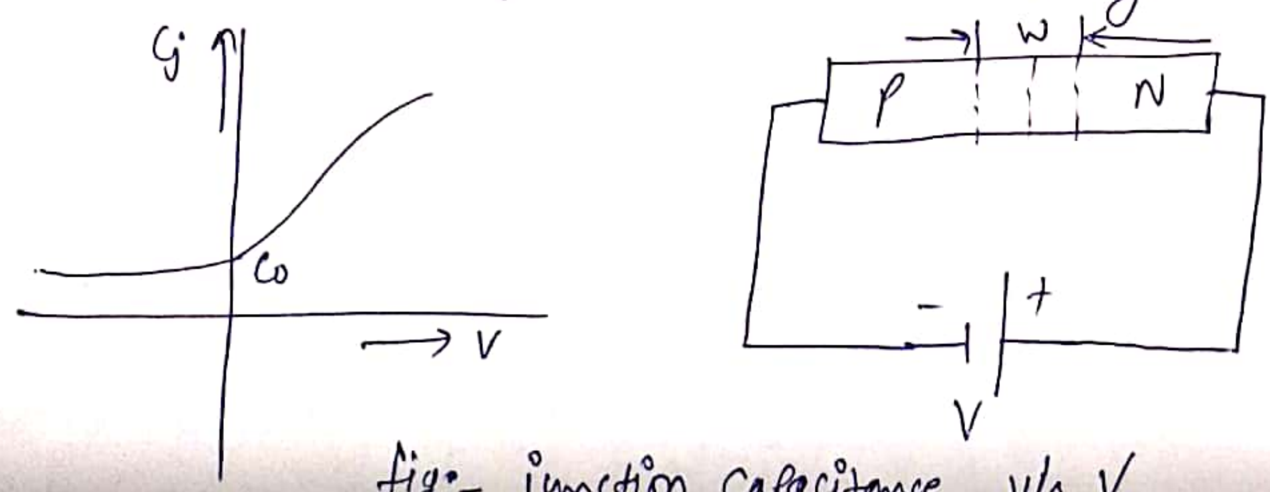


fig:- junction capacitance v/s V

∴ We know that $C_j \propto V_r^{-n}$ ——— (1)

Where C_j = Junction Capacitance

V_r = Reverse bias voltage

n = A parameter that decide the type of junction.

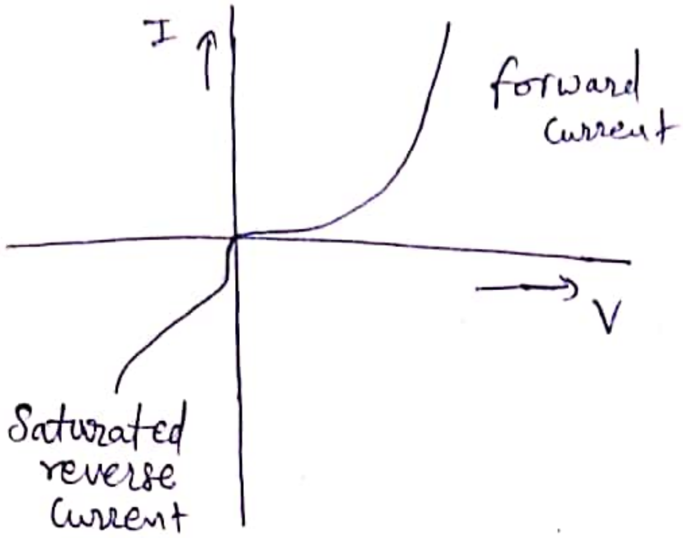


fig:- V-I Characteristics

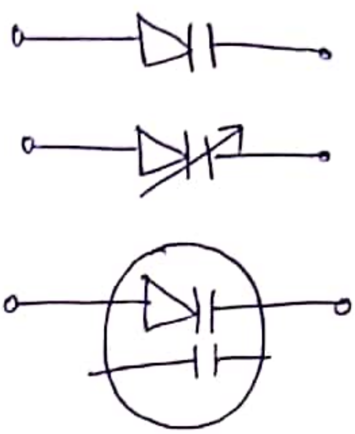


fig:- Commonly used symbols

The density of impurity concentration varies with distance on either side of the p-n junction. Let in a p^+n junⁿ with the donor density on the n-side varying as Bx^m, where B and m are constant and x is the distance from the metallurgical junction.

The one dimensional Poisson's equation is given by -

$$\frac{d^2V}{dx^2} = \frac{-qN}{\varepsilon} \quad \text{——— (2)}$$

where N is the generalised doping distribution and, as mentioned $N = Bx^m$. q is the charge of e^- and ε is the permittivity of the material. V is the voltage appear across the junⁿ.

∴ The eq^n. (2) can be ~~...~~ rewritten as:

$$\frac{d^2V}{dx^2} = \frac{-qBx^m}{\epsilon} \quad \text{--- (3)} \quad \left(\because E = -\frac{dV}{dx}\right)$$

or $$\frac{dE}{dx} = \frac{qBx^m}{\epsilon}$$

or $$\int_0^{E(x)} dE(x) = \frac{qB}{\epsilon}\int_w^x x^m dx$$

or $$E(x) = \frac{qB}{\epsilon}\left[\frac{x^{m+1}}{m+1}\right]_w^x$$

or $$-\frac{dV(x)}{dx} = \frac{qB}{\epsilon(m+1)}\left[(x)^{m+1} - (w)^{m+1}\right]$$

or $$\int_0^V dV(x) = \frac{qB}{\epsilon(m+1)}\int_0^w \left[(w)^{m+1} - (x)^{m+1}\right]dx$$

$$V = \frac{qB}{\epsilon(m+1)}\left[w^{m+1}\cdot w - \frac{w^{m+2}}{m+2}\right]$$

$$V = \frac{qB}{\epsilon(m+1)} w^{m+2}\left[1 - \frac{1}{m+2}\right]$$

$$V = \frac{qB}{\epsilon(m+2)} w^{m+2}$$

Thus, the width of the depletion layer for a Voltage V existing across the layer is

$$w = \left[\frac{(m+2)\epsilon V}{qB}\right]^{+\frac{1}{m+2}}$$

Now the capacitance of the junction.

$$C_j = \frac{\epsilon A}{W}$$

$$= \frac{\epsilon A}{\left[\frac{(m+2)\epsilon V}{qB}\right]^{+\frac{1}{m+2}}}$$

or $C_j = K V^{-\frac{1}{m+2}}$

Where K = constant = $\frac{\epsilon A}{\left[\frac{(m+2)\epsilon}{qB}\right]^{\frac{1}{m+2}}}$ and A is the effective area of the device.

We can say that

$$C_j \propto V_r^{-n}$$

Where

C_j = Junction capacitance

V_r = Reverse bias Voltage

n = A parameter that decide the type of junction $= -\frac{1}{m+2}$

Where $m = 0, 1$ or $-\frac{3}{2}$

Refer fig. for doping profile with these values of m.

$m = 0$; Abrupt Junction

$m = 1$; Linear Graded Junction

$m = -\frac{3}{2}$; Hyper Abrupt Junction.

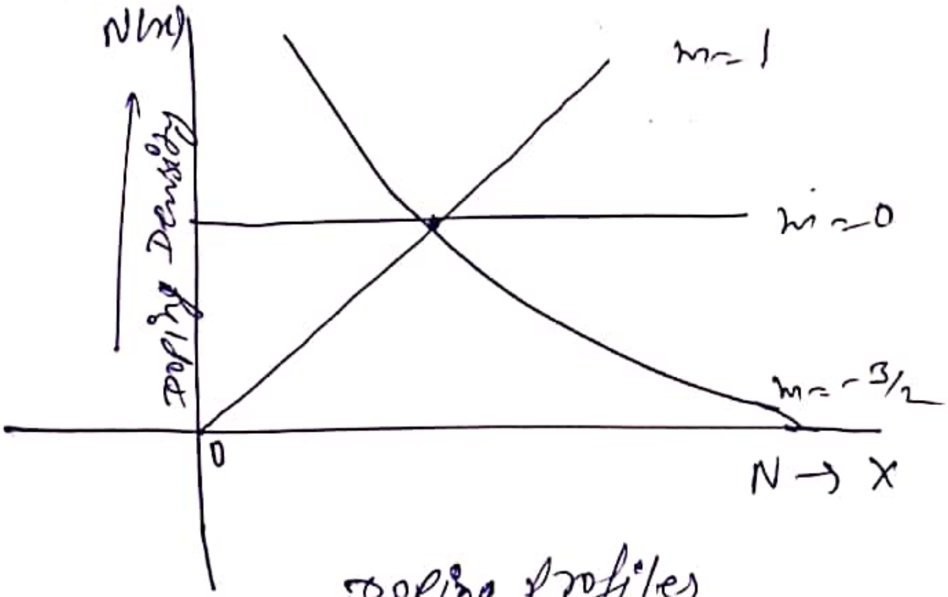
$\therefore$ $C_j \propto V_r^{-2}$ for a hyper abrupt junction. — (4)

(16)

When such a capacitance is used with an inductor 'L' in a resonant circuit, the resonant frequency varies linearly with the voltage applied to the varactor.

$$\omega_r = \frac{1}{\sqrt{LC}} \propto \frac{1}{\sqrt{V_r^{-n}}} \propto V_r \quad \text{for } n=2$$ — (5)

This clearly shows that C_j vs V_r curve can be effectively used for choosing specific doping profile and varactor diodes can be designed for specific applications.



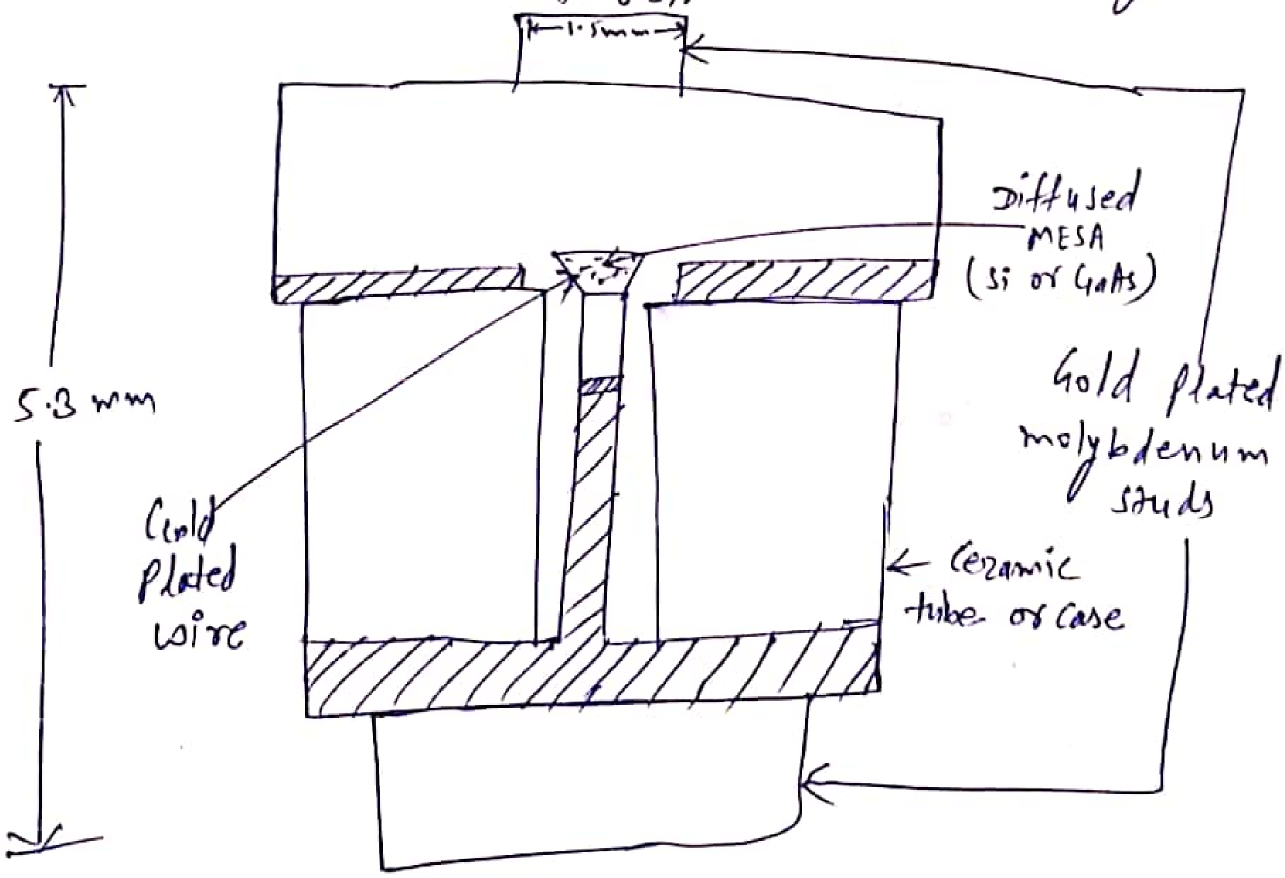
Doping profiles

In the graph, C_0 is the junction capacitance under no bias condition. With a reverse bias, the junction is depleted by mobile carriers resulting in capacitance i.e., the diode behaves as a capacitor with the junction acting as a dielectric between the two conducting materials. The width of the depletion region (w) increases with reverse bias and the capacitance decreases as the reverse bias increases. The avalanch region is never used as it is likely to destroy the device.

→ Construction of Varactor Diode :-

The constructional details of a Varactor diode are shown as in fig.

The diode encapsulation contains electrical leads attached to the semiconductor wafer and a lead to the ceramic case. Diffused junction MESA Si diode are widely used at microwave frequencies. They are capable of handling larger powers and large reverse breakdown voltages and have low noise. Frequency limit of Si diodes is upto 25 GHz. Varactors made of GaAs have high operating frequency (over 90 GHz) and better functioning at the lowest temperatures. However the manufacturing techniques are easier for Si.



Constructional details of varactor diode.

→ Equivalent Circuit :-

∴ The electrical equivalent circuit for a varactor diode is shown in fig.

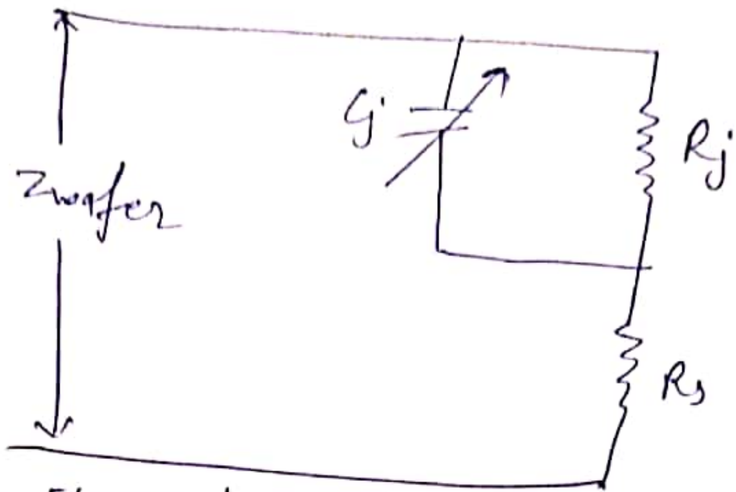


fig:- Electrical equivalent circuit for varactor diode.

→ C_j represents junction capacitance and is a function of applied bias.

→ R_j is the junction resistance and is a function of applied bias.

→ R_s is the series resistance including resistance of the wafer and the resistance of the ohmic electrical leads and is a function of applied bias.

→ At microwave frequencies R_j is of the order of 10 MΩ and may be neglected compared to capacitive reactance. Although variation in junction capacitance is the most important characteristic of a varactor diode, there are parasitic resistances, capacitances and conductances associated with every practical encapsulated diode.

The diode encapsulation contains electrical leads attached to the wafer and low loss ceramic cases as a mechanical support to the wafer. Because of these, equivalent circuit of fig. can be redrawn as a final equivalent circuit shown in fig.

Where C_c = Capacitance of Ceramic case
C_f = Fringe capacitance
L_s = Lead inductance
C_j = Junction capacitance.
R_s = Series Resistance.
R_j = 10 MΩ (neglected.)

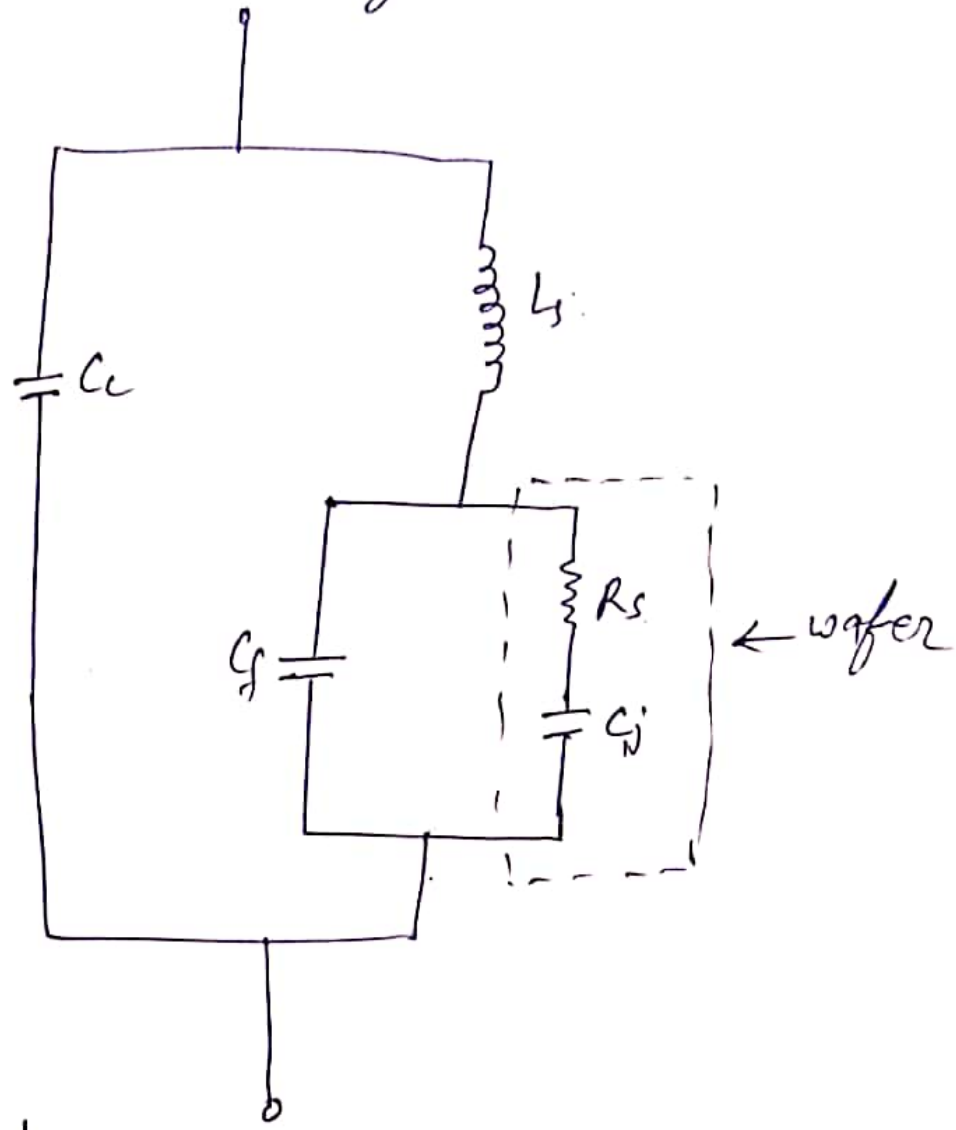


fig:- final equivalent circuit of varactor diode.

→ The parasitics should be kept as low as possible. for many applications there should be a large capacitance variation and small value of minimum capacitance and series resistances..

→ Figure of Merit of a Varactor :-

(i.) Static figure of Merit :-

(a.) Cut-off frequency :-

$$f_{cv} = \frac{1}{2\pi R_s C_{jv}}$$

C_{jv} → Junction capacitance at Voltage V

R_s → Series resistance of the diode.

f_{cv} for Si = 250 GHz
and for GaAs = 900 GHz.

At zero bias, $f_{co} = \frac{1}{2\pi R_s C_{jo}}$

f_c (pract.) = $\frac{f_c}{10}$

Si f_c = 25 GHz

GaAs f_c = 90 GHz

(b.) Quality factor :-

$$Q_v = \frac{f_{cv}}{f}$$

Q_v = Quality factor at a bias voltage 'v'

f_{cv} = Cut-off frequency at a bias voltage 'v'

f - Any frequency of interest at which Q_v is measured.

(ii.) Dynamic figure of Merit :-

(a.) Dynamic Cut-off frequency

$$f_c = \left(\frac{1}{C_{jmin}} - \frac{1}{C_{jo}}\right)\frac{1}{2\pi R_s}$$

where C_{jmin} = Capacitance of device near the reverse breakdown voltage.

C_{jo} = Junction Capacitance Corresponding to zero bias.

(iv). Dynamic quality factor (Q) :-

$$Q = \frac{S_1}{\omega R_s}$$

S_1 → the first fourier component of the time dependent elastant (reciprocal of capacitance)

$$\omega = 2\pi f$$

Also $Q = \tau \frac{f_c}{f}$

$$S_1 = \frac{1}{C_1} = \frac{\tau}{C_{jv}}$$

where $0.17 < \tau < 0.25$ for most varactor junctions

$\tau = 0.17$ for graded junction

$= 0.25$ for step junction

C_{jv} → Junction Capacitance at the operating bias.