Microwave Engineering

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Lecture 23

Schottky Diodes and Detectors and Tunnel Diodes

We have seen the functioning of the PN diode and also how we can make switches phase shifters using PN diode. Let us start a new topic Schottky diodes and detectors.

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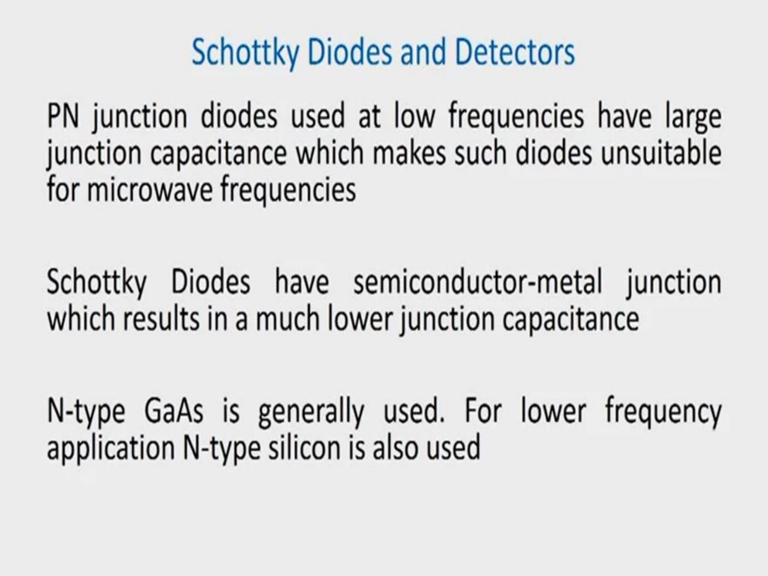

Schottky Diodes and Detectors

PN junction diodes used at low frequencies have large junction capacitance which makes such diodes unsuitable for microwave frequencies

Schottky Diodes have semiconductor-metal junction which results in a much lower junction capacitance

N-type GaAs is generally used. For lower frequency application N-type silicon is also used

PN junction diodes, which are used at low frequencies have large junction capacitance, and this makes such diodes unsuitable for microwaves frequencies. Schottky Diodes have semiconductor-metal junction, and this results in a much lower junction capacitance. Usually in the design of Schottky diodes N-types gallium arsenide is used, and for lower frequency operation N-type silicon is also used.

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Device model

$$I(V) = I_S(e^{\alpha V} - 1)$$

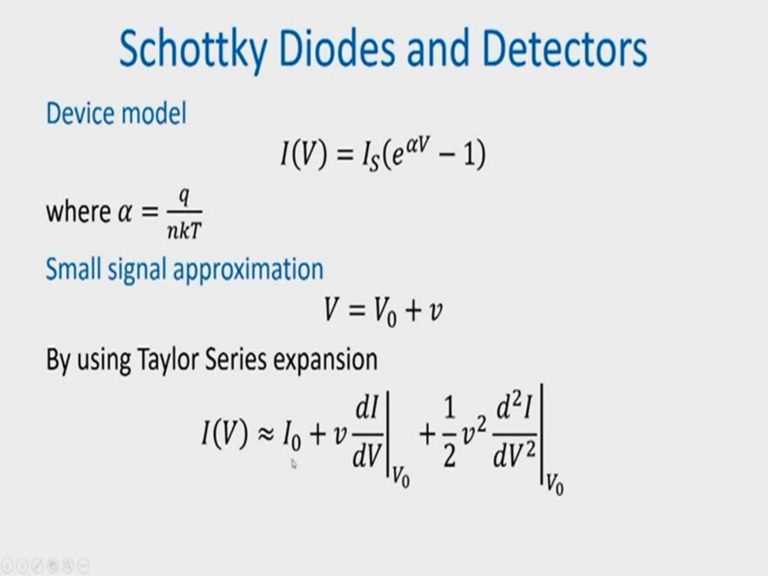
where $\alpha = \frac{q}{nkT}$

Small signal approximation

$$V = V_0 + v$$

By using Taylor Series expansion

$$I(V) \approx I_0 + v\frac{dI}{dV}\bigg|_{V_0} + \frac{1}{2}v^2\frac{d^2I}{dV^2}\bigg|_{V_0}$$



Schottky Diodes and Detectors

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Let us see how this device is modeled mathematically so the current I, flowing through a Schottky diode, can be written as I S e to the power alpha v minus 1 where this alpha is equal to q by nkT. n is the ideality factor for Schottky diodes; it is approximately 1.05. k is the Boltzmann's constant. T is absolute temperature in degree Kelvin and q is the electronic charge I_s is the saturation current, and it is very small so this is the devices model same as conventional diode, and we can see that when V is a large reverse voltage that means e to the power minus alpha V is very small then we will have I equal to minus of I_s, the reverse saturation current.

Now, this diode has a lower capacitance because of the metal-semiconductor junction. It has very fast response, and because of this faster response this diode is used for signal detection. So before we go for signal detection let us see the small-signal approximation that is used to describe the behavior of such diode. So let this voltage V consist of two parts V naught, which is the DC bias voltage and small v this is the AC component of the voltage, usually any signal variation that is present. Now, what we can do? We can go for Taylor Series expansion for this current I V around this DC voltage V naught.

So once this expansion is carried out I V can be written as I naught, I naught is the current when V equal to V naught plus small v d I d V at V equal to V naught plus half small v square d square I d V square at V equal to V naught there will be higher-order terms which are neglected and V approximate I V by these 3 terms.

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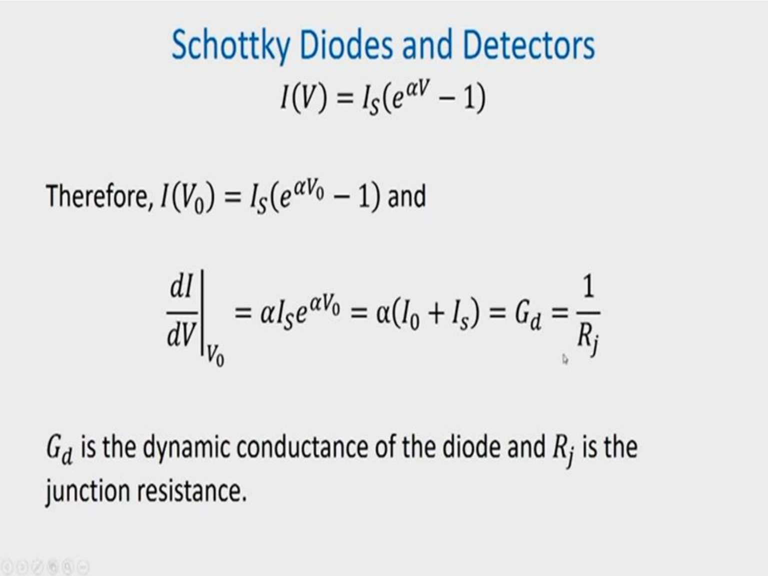
$$(V) = I_S(e^{\alpha V} - 1)$$

Therefore, $I(V_0) = I_S(e^{\alpha V_0} - 1)$ and

$$\left.\frac{dI}{dV}\right|_{V_0} = \alpha I_S e^{\alpha V_0} = \alpha(I_0 + I_s) = G_d = \frac{1}{R_j}$$



Schottky Diodes and Detectors

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G_d is the dynamic conductance of the diode and R_j is the junction resistance.

Now given I V equal to I_s, e to the power alpha v minus 1. Therefore I naught which is I V naught is I s, e to the power alpha v naught minus 1 and if you take the first derivative dI dV at v naught is alpha I s e to the power alpha v naught and this can be written as here we can see that I S e to the power alpha v naught is essentially I naught plus I s and therefore we can write this to be alpha I naught plus I_s and this is written as G_d and which can be written as 1 by R_j. Now here this G_d, it is the dynamic conductance of the diode because this is the ratio d I by d V so G_d is the dynamic conductance and R_j is the junction resistance, and this is reciprocal of the junction resistance.

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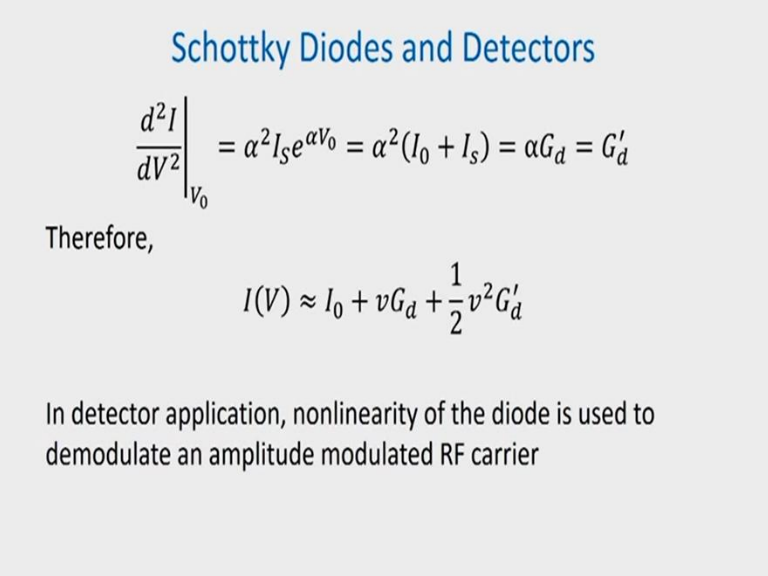
$$\left.\frac{d^2I}{dV^2}\right|_{V_0} = \alpha^2 I_S e^{\alpha V_0} = \alpha^2(I_0 + I_s) = \alpha G_d = G_d'$$

Therefore,

$$I(V) \approx I_0 + vG_d + \frac{1}{2}v^2 G_d'$$



Schottky Diodes and Detectors

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Therefore,

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In detector application, nonlinearity of the diode is used to demodulate an amplitude modulated RF carrier

Let us now evaluate the second derivative d square I dV square at V equal to V naught is alpha square I_s e to the power alpha V naught .Now, as before we can write, we can substitute I_s e to the power alpha v naught by I naught plus I s, so it becomes alpha square I naught plus I s which is alpha into G_d and this is represented as G_d dash.

Now, therefore, now we can have the diode current I V approximated as I naught vG_d plus half v square G_d dash. Now as we said we would use the Schottky diodes for signal detection because it is very fast response, and in such detector application, the nominate way of the diode is used to demodulate, and amplitude modulated RF carrier.

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The voltage applied to the diode can be expressed as

$$v(t) = v_0(1 + m\cos\omega_m t)\cos\omega_c t$$

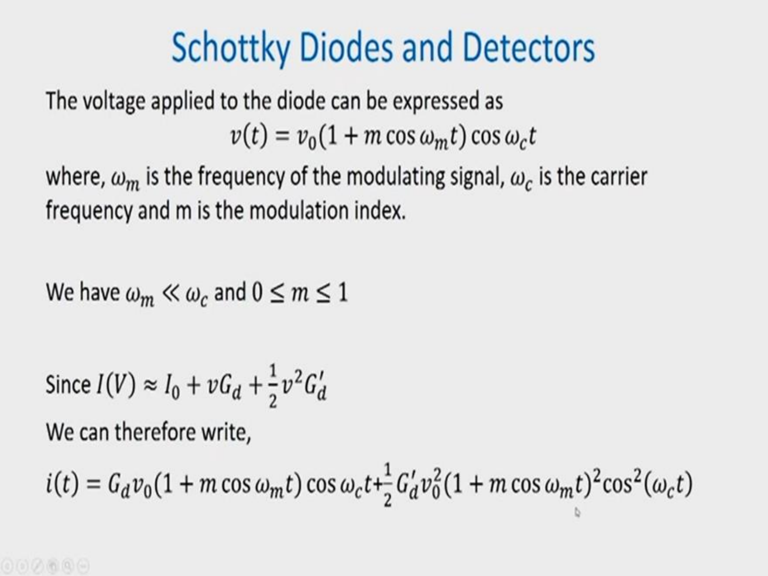
where, ω_m is the frequency of the modulated signal, ω_c is the carrier frequency and m is the modulation index.

We have $\omega_m \ll \omega_c$ and $0 \leq m \leq 1$

Since $I(V) \approx I_0 + vG_d + \frac{1}{2}v^2G_d'$

We can therefore write,

$i(t) = G_d v_0(1 + m\cos\omega_m t)\cos\omega_c t + \frac{1}{2}G_d' v_0^2(1 + m\cos\omega_m t)^2\cos^2(\omega t)$



Schottky Diodes and Detectors

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$i(t) = G_d v_0(1 + m\cos\omega_m t)\cos\omega_c t + \frac{1}{2}G_d' v_0^2(1 + m\cos\omega_m t)^2\cos^2(\omega_c t)$

Now when we are performing Demodulation operation, the voltage signal that is applied to the diode can be written as v_t is equal to v naught 1 plus m cos omega m t cos omega c t. Here omega m is the frequency of the modulating signal omega c is the carrier frequency, and m is the modulation index. We have omega m very small compared to omega c, and also modulation index m is less than 1. Please note that here we are considering a single tone modulation.

Now when this voltage is applied to the diode since IV is given by I naught vG_d plus half v square G_d dash, we can, therefore, write it is equal to G_d v naught 1 plus m cos omega mt cos omega ct plus half v naught square G_d dash 1 plus m cos omega mt square cos square omega ct. Once we have this current please note that it is the AC part of the current essentially IV minus I naught, and we can actually get the spectrum for this current, and it will have different frequency components.

It will have frequency components omega m 2 omega m, omega m plus omega c, omega c minus omega m, then 2 omega c like that. We want to detect our modulating signal which has a frequency omega m. So in order to detect the signal, we pass this IT through a low pass filter.

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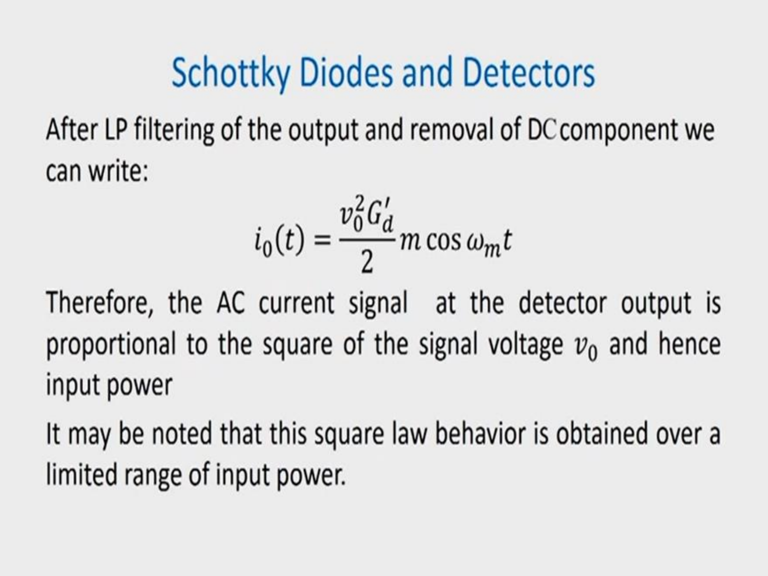
$$i_0(t) = \frac{v_0^2 G_d'}{2} m \cos \omega_m t$$



Schottky Diodes and Detectors

After LP filtering of the output and removal of DC component we can write:

$$i_0(t) = \frac{v_0^2 G_d'}{2} m \cos \omega_m t$$

Therefore, the AC current signal at the detector output is proportional to the square of the signal voltage v_0 and hence input power

It may be noted that this square law behavior is obtained over a limited range of input power.

So after low pass filtering of the output and removal of the DC component, we can write i naught t is equal to v naught square G_d dash by 2 m cos omega m t. So we find that the AC current signal at the detector output it is proportional to the square of the signal voltage v naught and therefore this current rate the detector output is proportional to the input power, you should naughte that this square law behavior of this type of Schottky diodes is obtained over a limited range of input power.

So over the range of input power, this diode can be used as a detector for modulated microwave signals. So we have discussed in brief the operation of the Schottky diodes and how it can be used as a detector. Let us naught consider another device, which is a tunnel diode.

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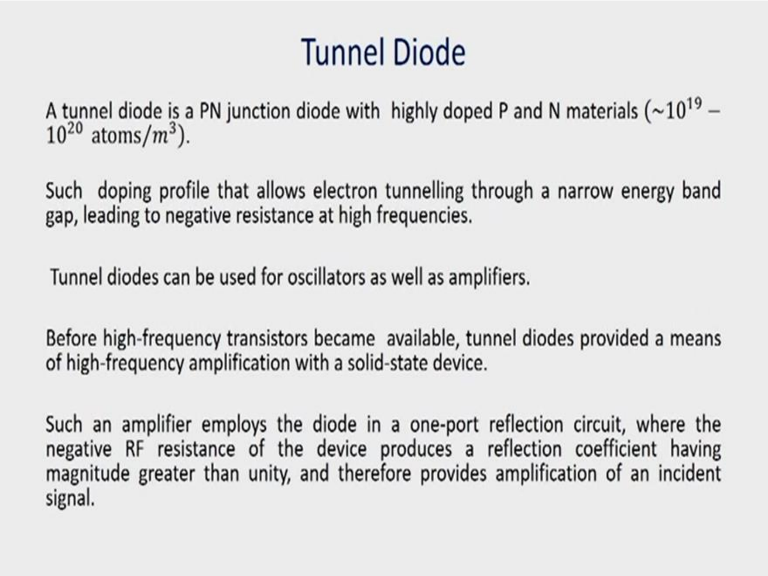

Tunnel Diode

A tunnel diode is a PN junction diode with highly doped P and N materials ($\sim 10^{19} - 10^{20}$ atoms/m^3).

Such doping profile that allows electron tunnelling through a narrow energy band gap, leading to negative resistance at high frequencies.

Tunnel diodes can be used for oscillators as well as amplifiers.

Before high-frequency transistors became available, tunnel diodes provided a means of high-frequency amplification with a solid-state device.

Such an amplifier employs the diode in a one-port reflection circuit, where the negative RF resistance of the device produces a reflection coefficient having magnitude greater than unity, and therefore provides amplification of an incident signal.

A tunnel diode is a PN junction, and the difference between normal diode is that the P and N regions are highly doped the doping concentration of the order of 10 to the power 19 to 10 to the power 20. Such doping profile allows electron tunneling through a narrow energy bandgap, leading to negative resistance at high frequencies. This type of diodes is also called Esaki diodes. Esaki invented the diodes operating on this principle of tunneling.

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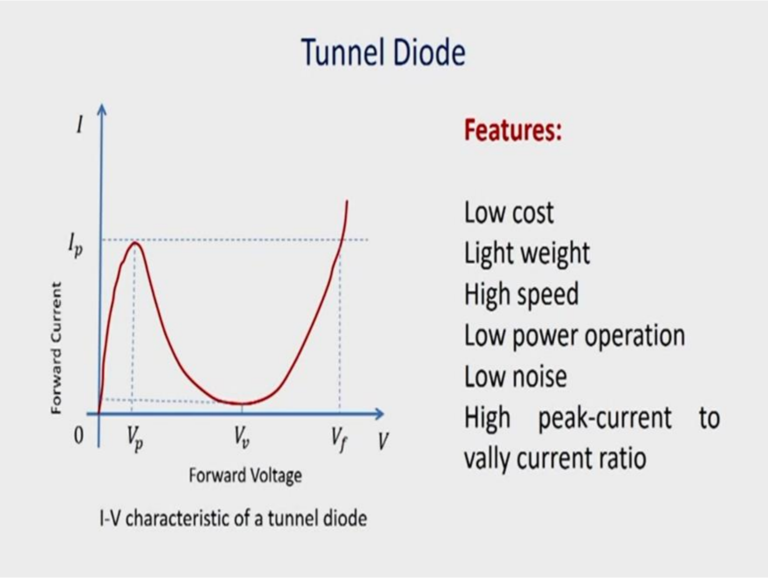

Tunnel Diode

I-V characteristic of a tunnel diode

Features:

Low cost
Light weight
High speed
Low power operation
Low noise
High peak-current to vally current ratio

Let us see the features of the tunnel diodes. They are low cost, lightweight, high speed, low power operation, low noise, and high peak-current to valley current ratio we will see. Now this diagram shows the IV characteristic of a tunnel diode. So here this point is the peak current we can see that initially as we increase the applied voltage to the diode the forward current increases then it reaches a peak value and then with the increase of voltage the current actually decreases and this decrease of current continues till some voltage which shown as V_v here.

So V_p is the voltage corresponding to peak current I_p, and this is the lowest current which is the valley current, and V_p is the voltage corresponding to the valley current and then beyond this voltage, if the applied voltage is increased, then the diode operates or functions as an ordinary diode with the current increasing exponentially with the rise of voltage. Now this region is the negative resistance region, which is very important for amplification of signals as well as for designing oscillators using tunnel diodes.

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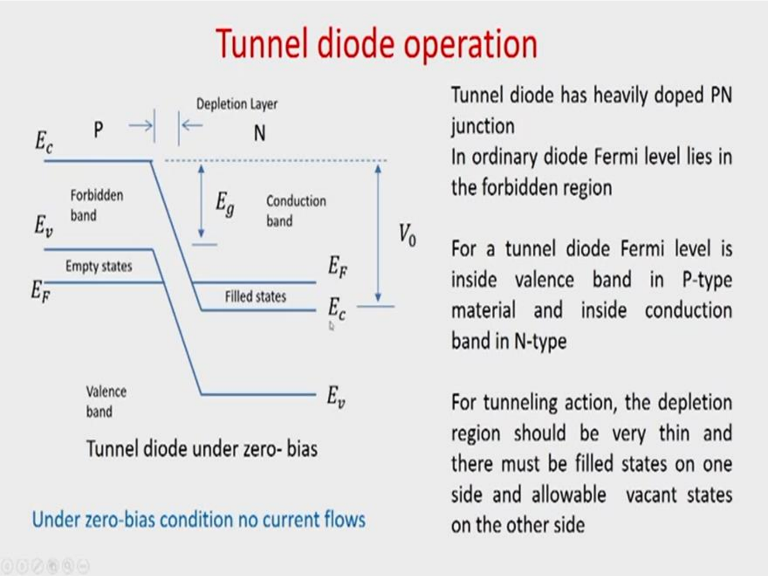

Tunnel diode operation

Tunnel diode under zero- bias

Under zero-bias condition no current flows

Tunnel diode has heavily doped PN junction

In ordinary diode Fermi level lies in the forbidden region

For a tunnel diode Fermi level is inside valence band in P-type material and inside conduction band in N-type

For tunneling action, the depletion region should be very thin and there must be filled states on one side and allowable vacant states on the other side

Let us now try to understand tunnel diode operation qualitatively. Here we can see that we have a PN junction and as we have mentioned that both P and N region they are highly doped and because of this heavy doping, we have empty states above the Fermi level in the P side, and we have filled states below the Fermi level in the N side. When no bias is applied the fermi is said the fermi level is said in both P and N-type material.

This difference may be noted because in ordinary P and N junction diode, Fermi level it lies in the forbidden region. Now here V 0 is the barrier voltage and E_g it is the forbidden bandgap. So we have already discussed tunnel diode has already heavily doped PN junction. For a tunnel diode Fermi level is inside valance band in P-type and inside conduction band in N-type.

Now for tunneling action, the depletion region should be very thin, this is the depletion region when the junction is formed we have the depletion region around the junction of P and N-type material, and there must be filled states on one side so here we have filled states in the N-type material and allowable vacant states on the other side. So if such a condition exists then the electrons can move from this or tunnel through the P-type material. Whenever a bias has applied, the electrons from these filled states will tunnel to and fill the empty states in the P-type material. So let us try to illustrate this situation.

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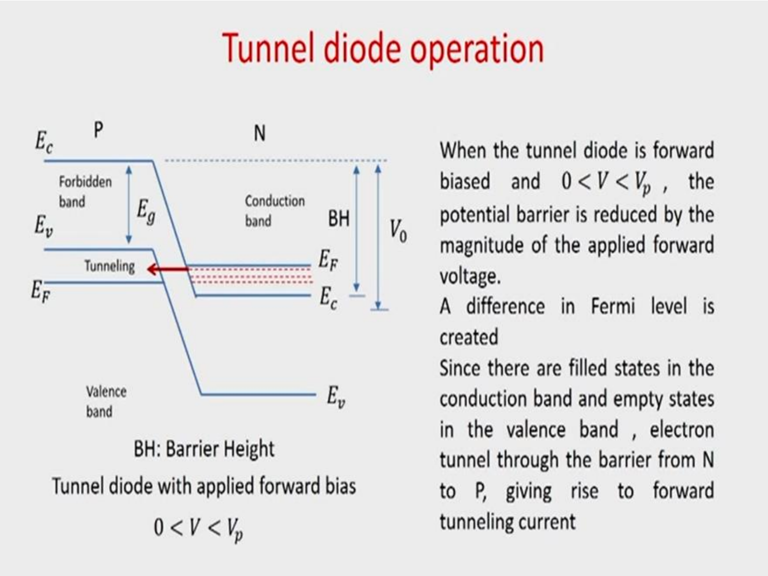

Tunnel diode operation

BH: Barrier Height

Tunnel diode with applied forward bias

$0 < V < V_p$

When the tunnel diode is forward biased and $0 < V < V_p$, the potential barrier is reduced by the magnitude of the applied forward voltage.

A difference in Fermi level is created

Since there are filled states in the conduction band and empty states in the valence band , electron tunnel through the barrier from N to P, giving rise to forward tunneling current

So here we can say that when a small bias voltage is applied that means V is between 0 to V_p now, we will have the barrier height reduced as compared to v naught, and therefore we will have this fill states, energy-wise this filled states in the conduction band aligning partially with the vacant states in the P-type material and electrons can now move directly from this filled states to the vacant states in P-type material through the tunneling process and when such moment of electrons takes place, this will result in a small current flowing in a device.

It is interesting to note that under 0 bias condition, there was no overlap as we increase the bias voltage this alignment of the filled state in conduction and vacant state in valance band this will increase. So when the tunnel diode is forward biased by a voltage V which is greater than 0 but less than V_p the potential barrier is reduced by the magnitude of the applied forward voltage. A difference in fermi level is created. Since there are filled states in the conduction band and empty states in the valance band, electron tunnel through the barrier, electrons tunnel through the barrier from N to P, giving rise to forward tunneling current.

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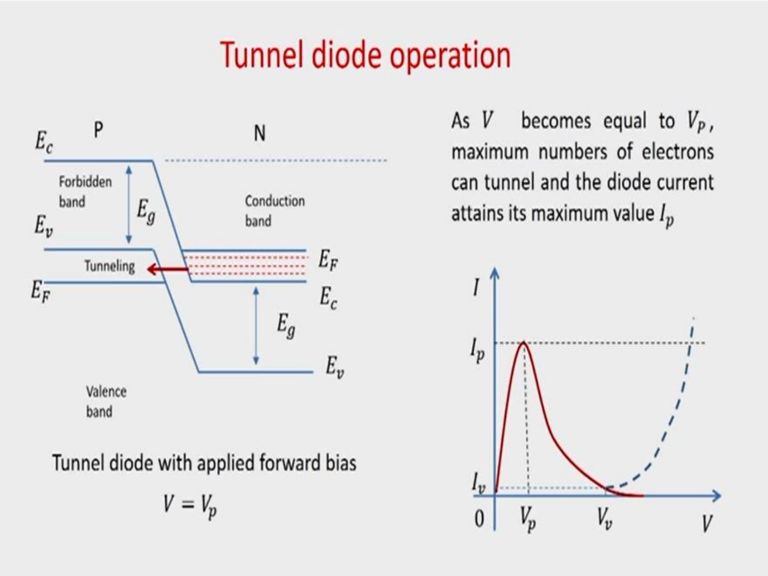

Tunnel diode operation

As V becomes equal to V_P, maximum numbers of electrons can tunnel and the diode current attains its maximum value I_p

Tunnel diode with applied forward bias

$V = V_p$

Now as we keep on increasing this applied voltage V, a situation will come when this filled band in the conduction band, when this filled bands in the N-type material will perfectly aligned with the empty states in the P-type material and will have maximum number of electrons tunneling from N side to P side and when V is equal to V_P that is why we get the maximum current or the peak current I_P. So, this red line is representing the current component that is being contributed by the tunneling mechanism and we can see that at V equal to V_P we have I reaching the peak current I P.

So we have the maximum number of electrons now can tunnel from N side to P side and the diode current attends its maximum value I_P

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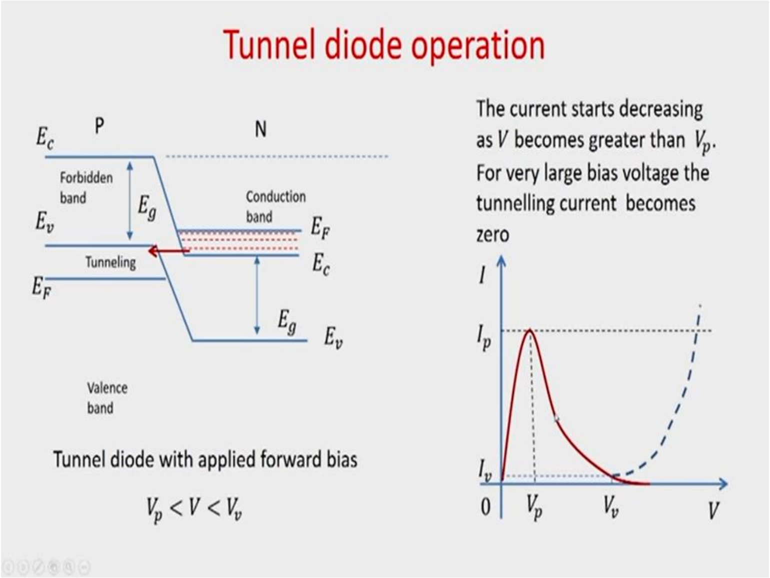

Tunnel diode operation

The current starts decreasing as V becomes greater than V_p. For very large bias voltage the tunnelling current becomes zero

Tunnel diode with applied forward bias

$V_p < V < V_v$

As we continue increasing the applied voltage V. Now we can see that the overlap (())(29:06) between the empty states in P and filled states in M, it gradually produces and this reduction results in a decrease in a current as now less number of electrons are available to tunnel from N to P region.

So, we see that this is the part from V_P to V_B the voltage increases but the current actually decreases and as we keep of increasing the voltage for very large bias voltage finally the tunneling current becomes 0, as I have mentioned there are two components of current here this one is the current component because of tunneling and this is normal diode operation the injection current.

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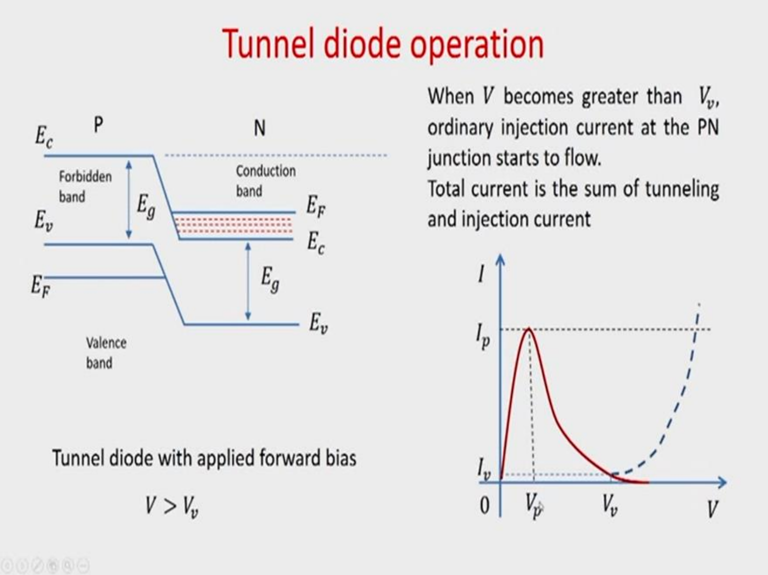

Tunnel diode operation

When V becomes greater than V_v, ordinary injection current at the PN junction starts to flow.

Total current is the sum of tunneling and injection current

Tunnel diode with applied forward bias

$V > V_v$

So when we increase the applied voltage V beyond V_V. Now there is no overlap between this empty and filled states and from here onward the electrons they will have to move over this potential barrier if these electrons are two migrate to the P region and therefore the normal carrier injection mechanism starts taking place and therefore the tunneling of electrons actually takes place over certain range of applied voltages and this phenomenon will happen only when the P and N sides they are very heavily doped favoring a situation where direct tunneling of electrons can take place.

So, when this V is greater than V_V, we find that here now the tunnel current the current due to tunnel effect decreases and normal injection current starts increasing, so when v becomes greater then V_V ordinary injection current at PN junction starts to flow, the total current is the sum of the tunneling of the injection current and IV is the minimum value of the current at applied voltage V_V, this is also the valley current, and this is the peak current. It may be noted that in this part the current increases with the voltage so in this region and also in this region we have the positive resistance region of operation of the diode whereas from V_V to V_P this region provides the negative resistance region of operation.

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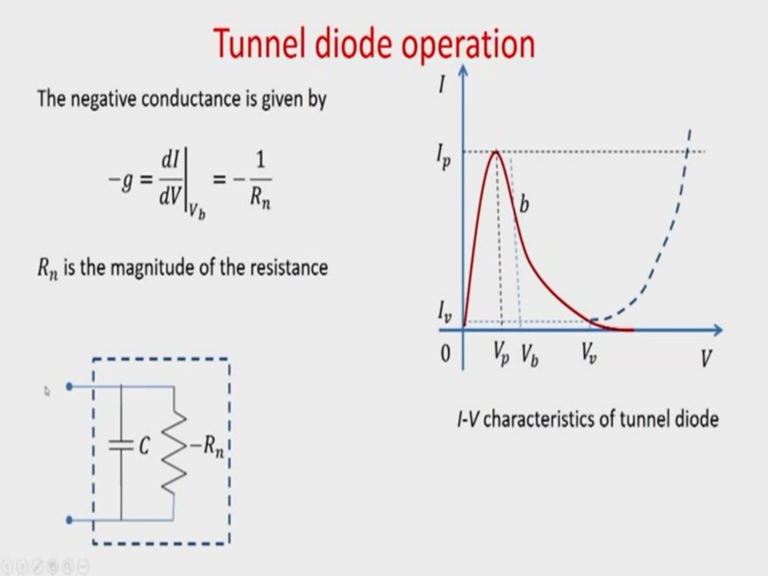
The negative conductance is given by

$$-g = \left.\frac{dI}{dV}\right|_{V_b} = -\frac{1}{R_n}$$

R_n is the magnitude of the resistance



Tunnel diode operation

The negative conductance is given by

$$-g = \left.\frac{dI}{dV}\right|_{V_b} = -\frac{1}{R_n}$$

R_n is the magnitude of the resistance

I-V characteristics of tunnel diode

Now let us consider in the negative resistance region a point b where the voltage is given by V_V then the negative conductance at this point is given by minus g is equal to dI by dV that means the change in current divided by the change in voltage at the point V_V and this can also be written as minus 1 by R_n where R_n is the magnitude of the negative resistance, please note that this g or R n, they will remain constant only over a small region because if I take another point here and calculate g the slope will be different, so all the for small changes in voltage this value of g will remain constant otherwise it will keep changing as we move from V_P to V_V.

In this region, the tunnel diode is also modelled as a negative resistance and the capacitance C representing the capacitance of the junction. There are, of course, other parasitic parameters at there the packing capacitance the inductance of the connecting lead these are not shown here, and this is the simplified equivalent circuit model of a tunnel diode.

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$$P_{out} = \frac{V^2}{R_L}$$

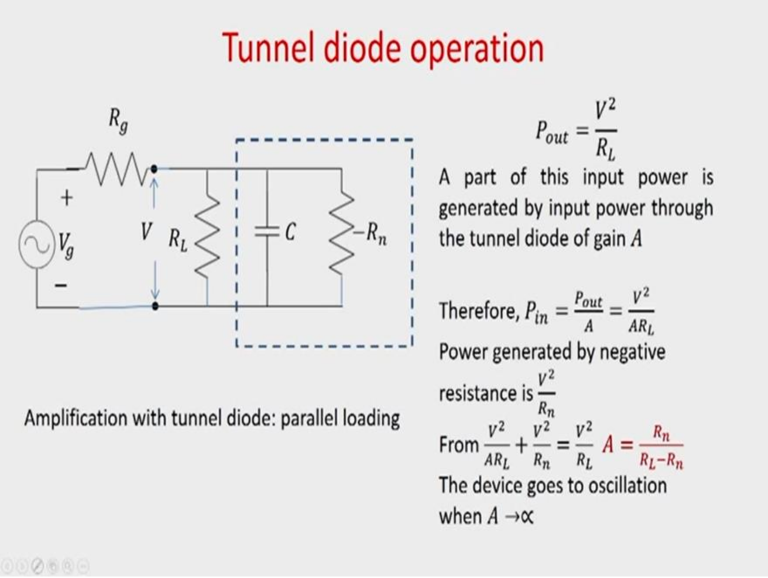
A part of this input power is generated by input power through the tunnel diode of gain A

Therefore, $P_{in} = \frac{P_{out}}{A} = \frac{V^2}{AR_L}$

Power generated by negative resistance is $\frac{V^2}{R_n}$

From $\frac{V^2}{AR_L} + \frac{V^2}{R_n} = \frac{V^2}{R_L}$ $A = \frac{R_n}{R_L - R_n}$

The device goes to oscillation when $A \to \infty$



Tunnel diode operation

Amplification with tunnel diode: parallel loading

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Power generated by negative resistance is $\frac{V^2}{R_n}$

From $\frac{V^2}{AR_L} + \frac{V^2}{R_n} = \frac{V^2}{R_L}$ $A = \frac{R_n}{R_L - R_n}$

The device goes to oscillation when $A \to \propto$

Let us now see how we can have amplification or oscillation form this type of tunnel diodes. Here we see the amplification with a tunnel diode when a load resistance R_L is loaded with a tunnel diode in a parallel manner. Now given that P_{out} is equal to v square by R_L and if A is the tunnel diode gain and then we can write P_{in} to v square by R_L into A, and also this being a negative resistance device, it will generate power.

A positive resistance it absorbs or dissipate power whereas a negative resistance device, it will supply or generate power so that is given by v square by R_n because it a parallel connection, so v is common for the load as well as the tunnel diode and from there equating v square A R_L plus v square by R_N equal to V square by R_L, we can find out A to B equal to R_N by R_L minus R_N.

So we can see this if R_L becomes equal to R_N, load resistance approaches the resistance of the negative resistance of the tunnel diode, in that case, A tends to infinity, and the device goes into oscillation. So, in brief, we have seen the operation of a tunnel diode, how it provides a negative resistance region and how this negative resistance region can be utilized for amplification or for certain load conditions; the device may give rise to oscillations as well. In the next topic we will consider a gun diode, which is called a transferred electron device.