Basic Electronics
(Module – 1 Semiconductor Diodes)
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Lecture - 2
PN Junction Diodes

You know what a P type semiconductor and an N type semiconductor is. What will happen when you combine P type semiconductor and N type semiconductor? That means you sandwich them or make a junction between P type and N type. That we will be discussing today. You have P and N type of semiconductors combined together by some appropriate scheme like ion implantation or diffusion. This process is not mechanical mind it; not to disturb the crystalline structure of the silicon or germanium semiconductor which is the base material. Properly formed P-N junction will be having P type on one side and N type on the other side.

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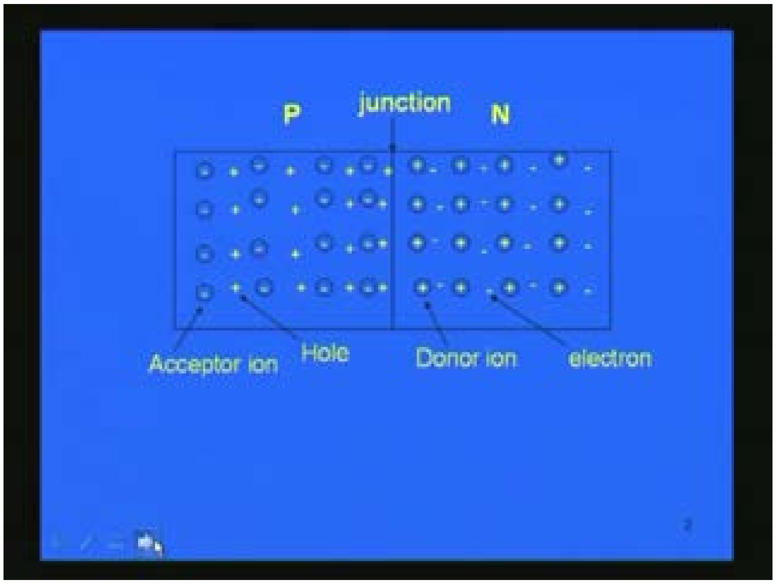

If we consider this P type and N type semiconductor making a junction in between them then here we can notice that the P type semiconductor has the acceptor ions as well as the carriers which are holes, positively charged carriers and N type semiconductor has donor ions and electrons. We have majority carriers, holes in the P type and the electrons are majority carriers in N type along with the acceptor ions on the P side and the donor ions in the N side which are negatively and positively charged respectively. There will be a difference in concentration or there will be a concentration gradient of holes from P to N side as well as there will be concentration gradient of electrons from N to P side. Whenever there is a concentration gradient then the carriers that is holes and electrons will try to flow from a higher concentration region to a lower concentration region. Just like whenever there is pressure difference in the water level between two places then higher pressure water will flow down to the place where pressure of water is low. Similarly because of this difference in concentration the holes will start moving from P type to N type and this process is called diffusion.

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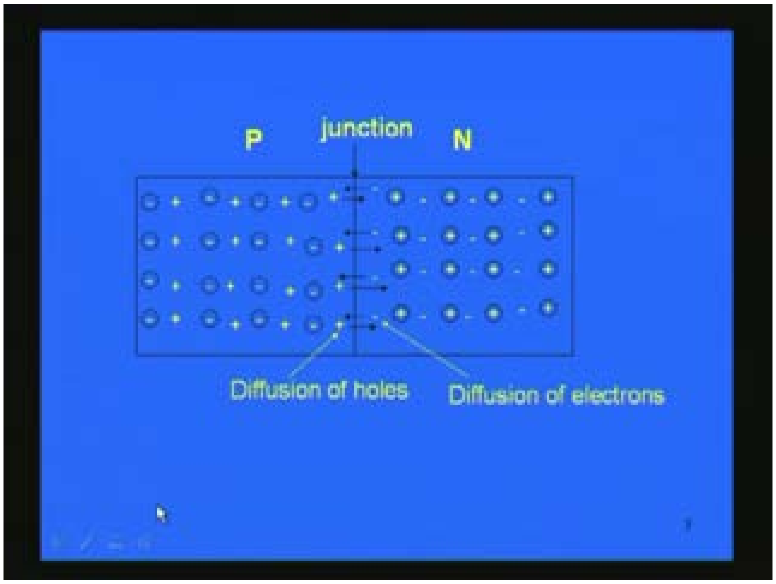

P

junction

N

Diffusion of holes

Diffusion of electrons

Here these holes will be crossing over the junction from left side to the right side and the electrons will be crossing the junction from the right side to the left side. This process is called diffusion. Diffusion of holes and diffusion of electrons will take place whenever you bring P-N junction together. As these carriers, holes from left side cross over to the right side and electrons cross over from right side to left side what will happen is that there will be recombination of charges because holes will be recombined with free electrons and electrons will be recombining with free holes. Then because of the recombination of these charges now what will happen is that the ions that means the acceptor ions on the P side and the donor ions in the N side they will be now surfaced out. Surfaced out means they are now uncovered because earlier, in this case, you have seen that every acceptor ion has a hole which is positively charged along with it. The charge neutrality was maintained. Similarly in the N side, donor ion has a free electron attached to it. That means there also charge neutrality is conserved.

But now because of the recombination of the holes and electrons these charges of the ions now become uncovered. That means along with it there are no carriers. There are now uncovered negative charge on the P side and then uncovered positive charge on the N side. That is why these bound charges will be forming layers of negative charge on the P side and positively charged layer on the N side. This region where there will be no mobile charges only bound or fixed charges are there this region is called a depletion region or it is also called space charge region. This region is devoid of the free carriers.

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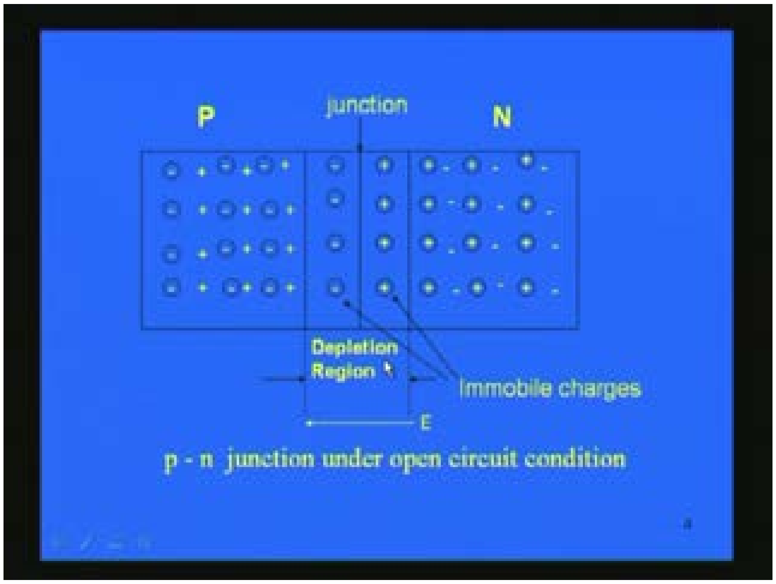

p - n junction under open circuit condition

Under open circuit condition that means we are not connecting these P-N junction to any circuit; it is open circuited. We will have in the depletion region only immobile charges. These immobile charges are forming two layers negatively charged layer on the left side that means P side and positively charged layer on the right side. That means a potential is developed and the potential is positive on the right side here and negative on the left side. This potential will be now preventing or it will be stopping further movement of free charge carriers because as this side is positive and this side is negative these holes are now repelled by this positive charge on the right side. That means these holes cannot now cross over the junction and come to the N side because this will be stopped or prevented by the positive potential which is developed. This is also called barrier potential because of the fact that it is a barrier to further movement. These holes cannot move to the right as well as the electrons cannot move from N side to P side because these bound negatively charged layer on the left side or the P side will be preventing it from crossing over to the P side.

This potential is creating a field. That field is say E. This field will be produced and this potential barrier will be preventing any further movement of holes and electrons. There are also thermally generated minority carriers which are the electrons on the P side and holes on the N side. These are thermally generated. This E is developed because of this crossing over of holes and electrons and because of this barrier potential being developed the direction of the field is such that it is positive on this side and negative on this side. These electrons which are minority carriers for the P type will be attracted by this field because it is positive towards right and the minority carriers which are holes will be attracted by the negative potential. Because of this field being produced there will be drift of these minority carriers and due to the drift of these minority carriers a current will be flowing.

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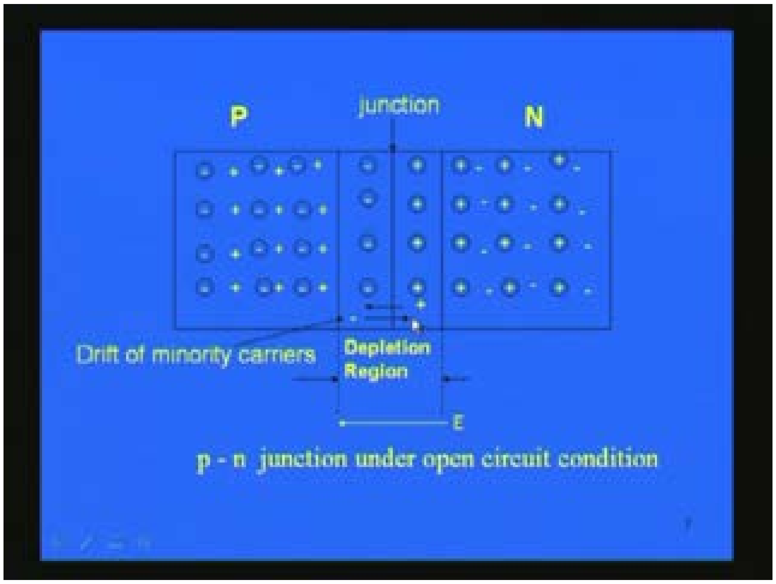

p - n junction under open circuit condition

The direction of this current is just opposite to the direction of the diffusion current. Because of diffusion the current was from left to right and because of drift the current is from right to left. So open circuited p-n junction will have no current that is total current will be zero because to reach the steady state or stable condition the diffusion current is equal to the drift current. Finally the total current in this open circuited p-n junction will be zero. We have seen that the diffusion current is due to the concentration gradient and diffusion of holes take place from P side to N side and the diffusion of electrons from N side to P side and the holes and electrons recombine because of this diffusion and they uncover the bound charges.

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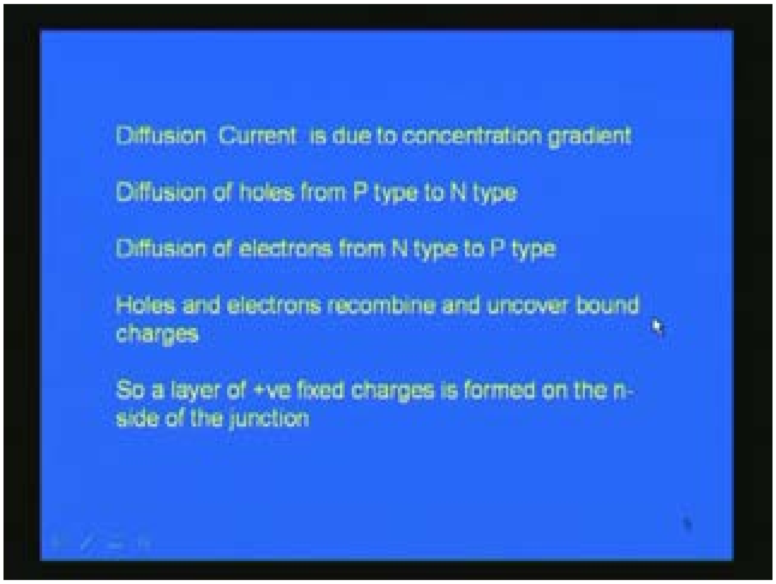

Diffusion Current is due to concentration gradient

Diffusion of holes from P type to N type

Diffusion of electrons from N type to P type

Holes and electrons recombine and uncover bound charges

So a layer of +ve fixed charges is formed on the n-side of the junction

A layer of positive fixed charges is formed on the N side of the region giving rise to a potential and that potential is known as built in potential or sometimes it is named as barrier potential.

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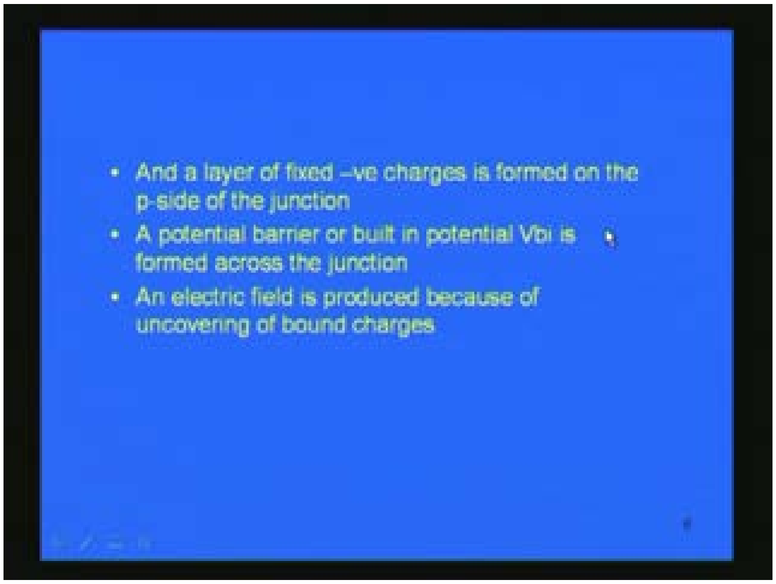

- And a layer of fixed –ve charges is formed on the p-side of the junction
- A potential barrier or built in potential Vbi is formed across the junction
- An electric field is produced because of uncovering of bound charges

This uncovering of bound charges produced an electric field. This electric field will now act upon the minority carriers so drift current will be produced and under steady state diffusion current is equal to drift current. So net current will be zero under open circuit.

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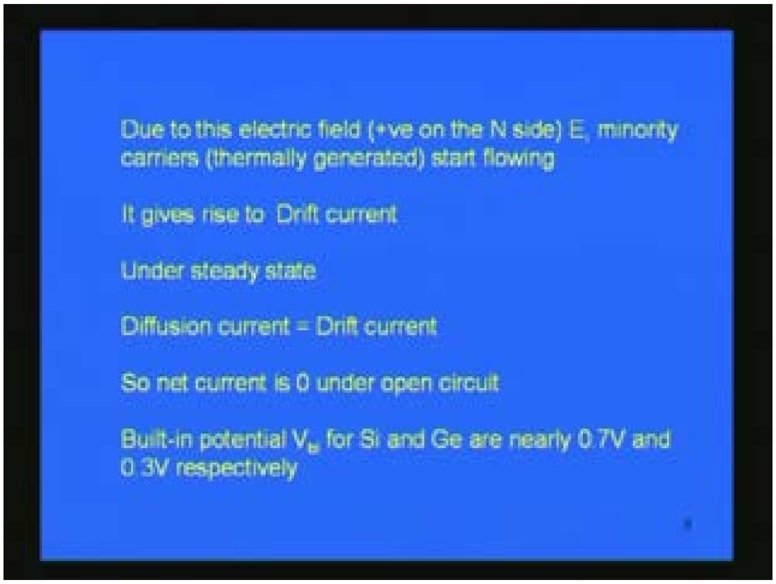

Due to this electric field (+ve on the N side) E, minority carriers (thermally generated) start flowing

It gives rise to Drift current

Under steady state

Diffusion current = Drift current

So net current is 0 under open circuit

Built-in potential V_B for Si and Ge are nearly 0.7V and 0.3V respectively

This built-in potential for silicon and germanium are nearly 0.7 volt and 0.3 volt. The barrier potential is such that if we consider from the P side it will be rising and we get a maximum value of this built-in potential which is V_{bi}.

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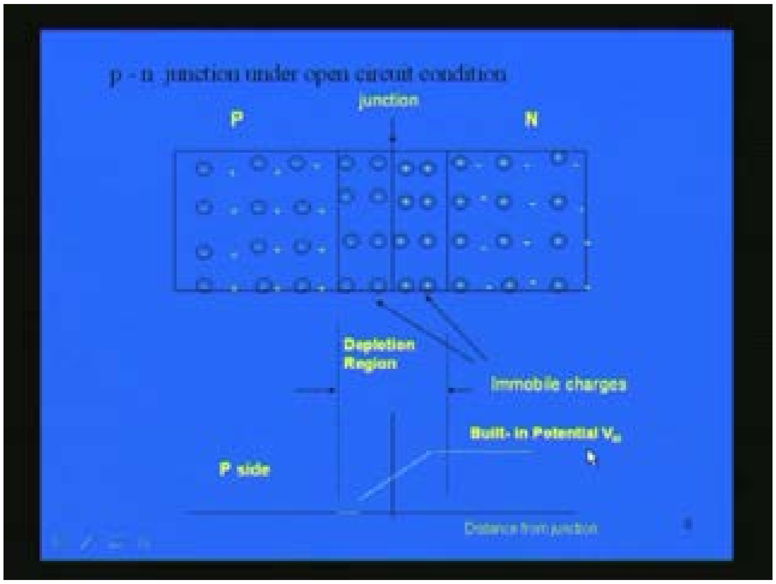

p - n junction under open circuit condition

This built-in potential has an expression given by kT by e and natural logarithm of the product of N_AN_D, which carry their usual meaning, that is the concentration of the acceptor atoms and the concentration of the donor atoms divided by n_i square which is intrinsic carrier concentration.

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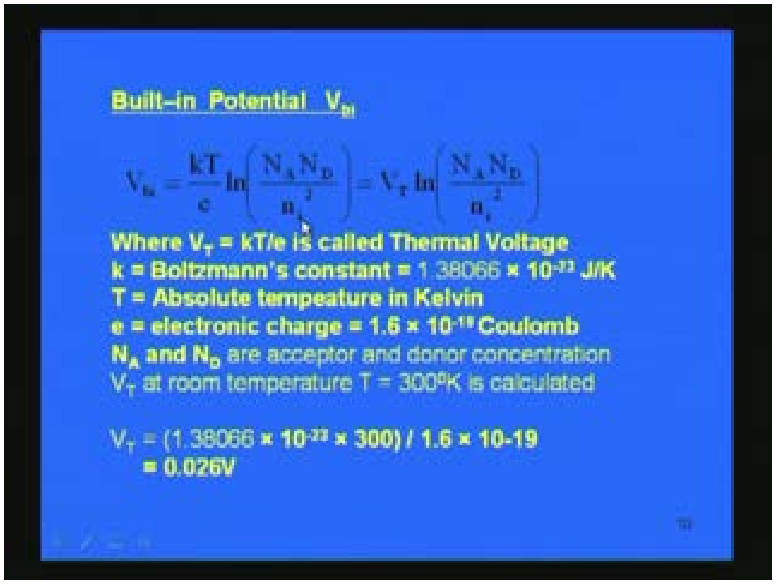

Built–in Potential V_{bi}

$$V_{bi} = \frac{kT}{e}\ln\left(\frac{N_A N_D}{n_i^2}\right) = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

Where V_T = kT/e is called Thermal Voltage

k = Boltzmann's constant = 1.38066 **× 10^{-23} J/K**

T = Absolute tempeature in Kelvin

e = electronic charge = 1.6 × 10^{-19} Coulomb

N_A and N_D are acceptor and donor concentration

V_T at room temperature T = 300°K is calculated

V_T = (1.38066 **× 10^{-23} × 300) / 1.6 × 10-19**

= 0.026V

This term kT by e can be expressed as thermal voltage, V_T which is equal to kT that is Kelvin temperature divided by electronic charge and K is Boltzmann constant. This constant is 1.38066 into 10 to the power of -23 joule per Kelvin. T is absolute temperature in Kelvin, electronic charge you know is 1.6 into 10 the power of -19 coulomb. We consider room temperature that is 300 degree Kelvin. Generally all calculations are done at room temperature unless and until mentioned. V_T, the thermal voltage can be calculated using this constant and the electronic charge is 1.6 into 10 to the power of -19 and this is Boltzmann constant. It will be giving a voltage of 0.026 volt at room temperature.

The width of depletion region is given by an expression under root two eta s divided by q into 1 by N_A plus 1 by N_D into V_{bi}. The barrier potential or built-in potential has an effect on this depletion layer given by this expression where this eta s is the electrical permittivity of silicon.

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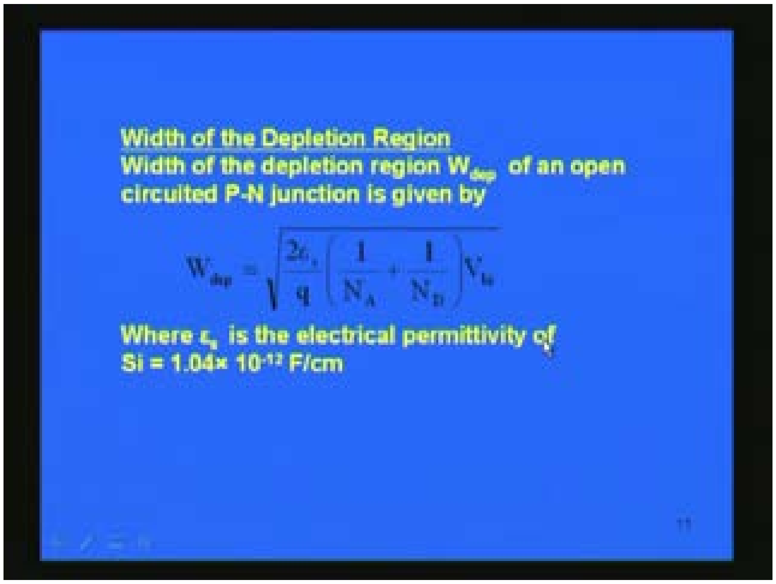

Width of the Depletion Region

Width of the depletion region W_{dep} of an open circuited P-N junction is given by

$$W_{dep} = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_{bi}}$$

Where ε_s is the electrical permittivity of Si = 1.04×10^{-12} F/cm

If I consider this silicon material it is 1.04 into 10 to the power of -12 Farad per centimeter. If we know these two expressions we can find out what will be the value of this barrier potential or built-in potential and depletion layer width for a p-n junction.

Let us consider a silicon p-n junction at room temperature 300 degree Kelvin and it is doped with N_A is equal to 10 to the power of 16 per centimeter cube in the P region and in the N region the doping concentration is 10 to the power 17 per centimeter cube and intrinsic carrier concentration for silicon at room temperature is 1.5 into 10 to the power 10 per cm cube. This value we already know. We can find out the built-in potential V_{bi} using these values. This expression which we have with us is V_T natural logarithm N_AN_D by N_i square.

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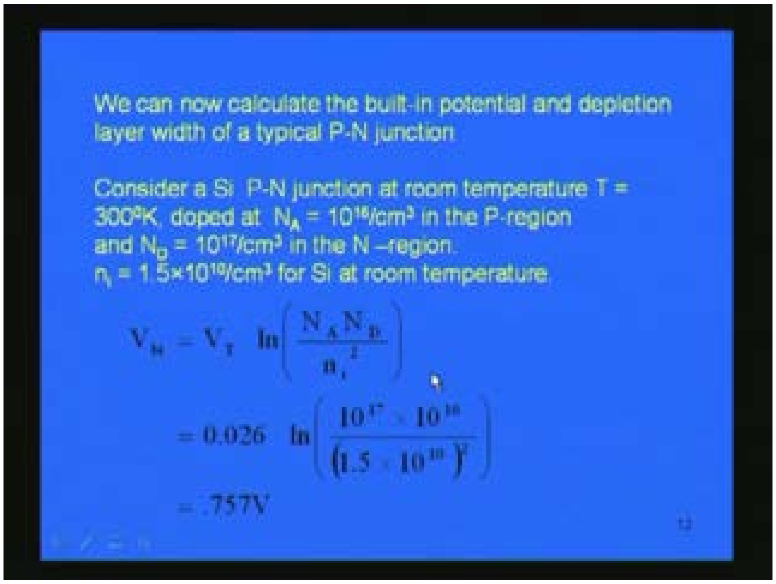

We can now calculate the built-in potential and depletion layer width of a typical P-N junction

Consider a Si P-N junction at room temperature T = 300°K, doped at $N_A = 10^{16}/cm^3$ in the P-region and $N_D = 10^{17}/cm^3$ in the N –region.
$n_i = 1.5\times10^{10}/cm^3$ for Si at room temperature

$$V_{bi} = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$
$$= 0.026 \ln\left(\frac{10^{17}\times10^{16}}{(1.5\times10^{10})^2}\right)$$
$$= .757V$$

For this particular example if we substitute these values we will be substituting thermal voltage with 0.026 volt and natural logarithm of N_AN_D and N_i being substituted for this example will give us a built-in potential around 0.757 volt. For silicon at room temperature we will be getting a built-in potential around 0.7 volt. Similarly we can calculate the width of the depletion layer for this example given by this expression and here we will be substituting all those information given to us like eta s and q. This N_AN_D already we have with us and V_{bi} the barrier potential or built-in potential we have found after calculation that is 0.757 volt.

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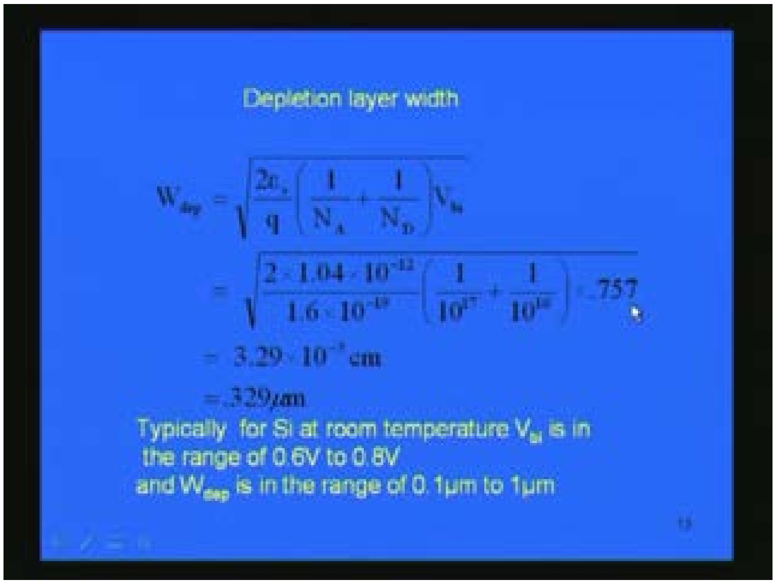

Depletion layer width

$$W_{dep} = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)V_{bi}}$$
$$= \sqrt{\frac{2\times1.04\times10^{-12}}{1.6\times10^{-19}}\left(\frac{1}{10^{17}}+\frac{1}{10^{16}}\right)\times.757}$$
$$= 3.29\times10^{-5}\,cm$$
$$= .329\mu m$$

Typically for Si at room temperature V_{bi} is in the range of 0.6V to 0.8V
and W_{dep} is in the range of 0.1μm to 1μm

Calculation of this expression under root will be giving us 0.329 micrometer which is the width of the space charged region or depletion region for this particular silicon p-n junction. At room temperature silicon has a barrier potential or built-in potential in the range of 0.6 to 0.8 volt and the depletion region width is in the range of 0.1 micrometer to 1 micrometer. Because temperature plays a role you will be getting different value for different temperatures but we are taking at room temperature, at 300 degree Kelvin.

What will happen if we connect a voltage with polarity positive to the P and negative of the voltage to N. This particular biasing is known as forward bias condition. In forward biasing we connect P of the p-n junction to positive of the voltage supply and N to the negative of the voltage supply. Whenever you are applying a voltage as positive we are connecting to the end of the P side. This positive terminal will be repelling these holes. Similarly this negative terminal will be repelling the electrons in the N side. These holes will be coming towards the junction and it will be neutralizing the atoms. The acceptor ions on the P side will be neutralized; some of them will be neutralized. Similarly these electrons will be neutralizing the donor atoms which are positively charged. That means we will be now having a lesser depletion region because depletion region contains all the uncovered charges only. As the holes will be moving to the right the depletion region will get reduced and if you consider from the point of view of the built-in potential we are now applying a voltage with this polarity plus to this side and negative to this side and our built-in potential is positive on this side, N side. We have the built-in potential V_{bi} reduced by this amount V. Our built-in potential is reduced so more and more holes will be easily crossing over to the N side because it will offer less potential barrier because it has been reduced by this voltage. So more and more holes will be crossing over to this N side and more and more electrons will be crossing over to the P side.

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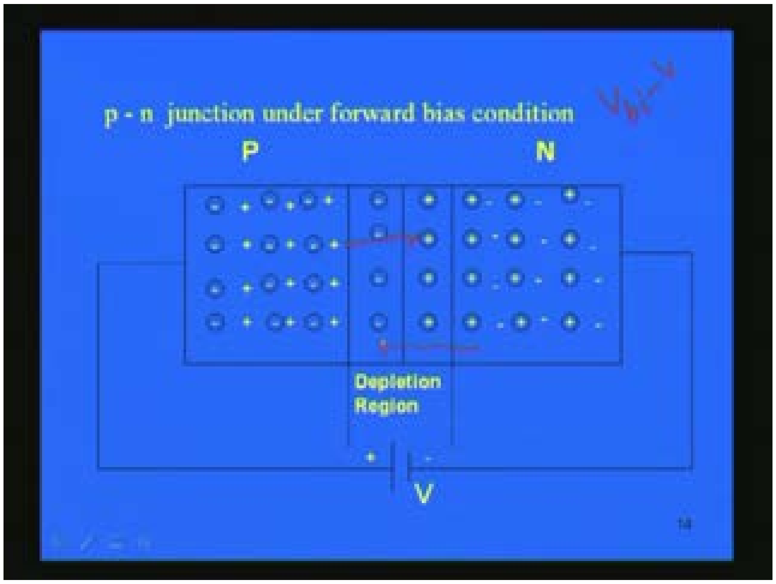

p - n junction under forward bias condition

That means when we forward bias a p-n junction there is easier flow of holes and electrons from P and N side. That is the diffusion current will be increasing and with a very small change in the voltage being applied we can have a very high exponential growth in the current in the forward bias condition.

If we consider the reverse that is if we connect negative of the voltage to the P side and positive of the voltage to the N side it is called reverse bias condition. What will happen is that now as this negative terminal of the supply is connected to P type these holes will be attracted by this negative polarity. So they will be moving away from the junction. Similarly these electrons will be attracted by this positive terminal of the battery. So these electrons will be moving away from the junction. This is the junction. It will be going further away and away from the junction and as a result of that more and more uncovering of the fixed or bound charges will take place because these carriers will move away they will be surfaced out.

As a result of this the depletion region will be now extending; it will be increased and if we look from the barrier potential point of view or the built-in potential point of view, the polarity is positive this side and negative this side and we are now having this voltage applied with this polarity negative to the P and positive to the N. Now the barrier potential will be increased. It was V_{bi} earlier. It will be increased by this amount $V_{bi}+V$. That means it will be offering very high resistance to flow of the charge carriers. That is diffusion will not be taking place now. So the diffusion current is zero. Only current which will be flowing but that also in micron order is due to the minority carriers because minority carriers are holes in the N type and electrons in the P type. The positive terminal of the battery will be repelling these minority carriers which are holes from N side to cross over. Similarly negative terminal will be repelling the electron to cross over. So the current which is called reverse saturation current will flow. I_S is the reverse saturation current that will flow in this direction which is opposite to the forward biased current. But this order is very small. The minority carrier concentration is very less. This is very small and it is dependent mainly on the temperature.

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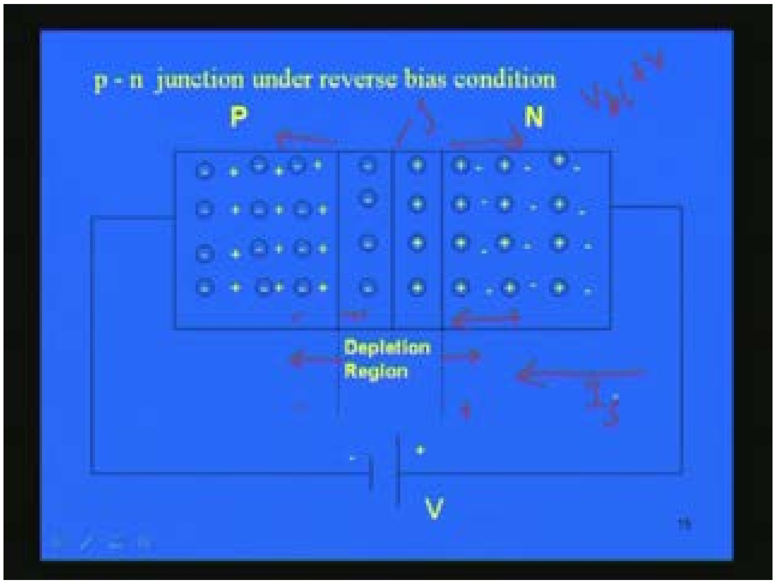

p - n junction under reverse bias condition

It will be increased if we raise the temperature because you know that increase of temperature will result in production of more and more minority carriers. More and more electrons will be breaking away from the covalent bonds of silicon or germanium and more and more electron hole pairs are created when you increase the temperature. Other than that the applied voltage does not have much effect on this reverse saturation current.

This p-n junction actually is the backbone of the semiconductor diode. Semiconductor diode is formed by bringing the P type and N type materials together. Basically this p-n junction forms a diode. This diode is formed by special processes. Just mechanically bringing this P and N together will not serve the purpose because the crystalline structure will have to be maintained. It should not be disturbed. Electrical characteristic should not be disturbed and that is possible only if we do the fabrication using standard techniques and the processes which are used for this type of semiconductor diode formation are generally alloying, diffusion or ion implantation. The symbol for a semiconductor diode using p-n junction is this one. This side is P and this side is N. This is the diode symbol.

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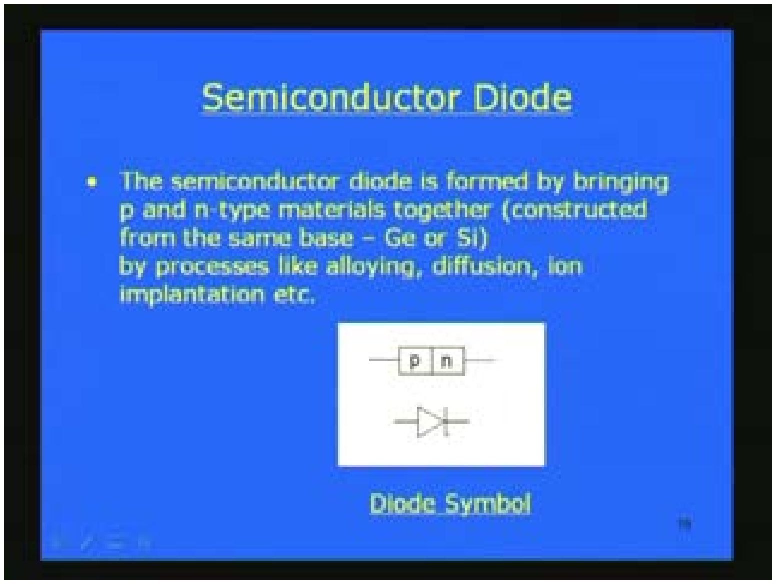

Semiconductor Diode

- The semiconductor diode is formed by bringing p and n-type materials together (constructed from the same base – Ge or Si) by processes like alloying, diffusion, ion implantation etc.

Diode Symbol

Diode has immense application in electronics starting from rectification. If you want to produce a DC voltage from an AC voltage we use semiconductor diode. Basic property which is exploited is rectification and many different devices use diodes. We will be touching up on some of them. In the forward bias condition, this I_D is the current flowing and V_D is the voltage across this p-n junction. In the forward bias positive is connected to P and negative is connected to N and the reverse bias has just the opposite; positive is connected to N and negative is connected to P and the current which flows in the reverse bias condition is reverse saturation current that is denoted by I_S.

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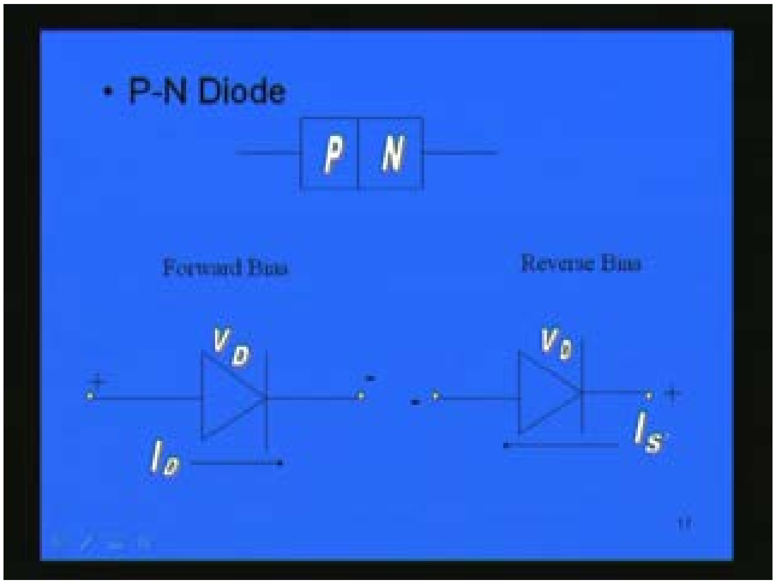

- P-N Diode

What will be the relationship between the current and voltage in a semiconductor diode? That is an important relationship we must remember. This is given by I_D equal to I_S into exponential K times V_D divided by T_k minus 1.

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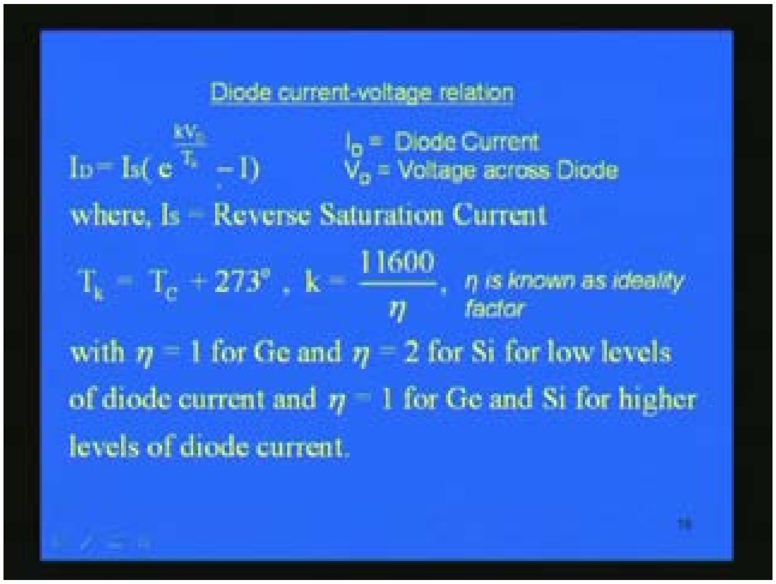

Diode current-voltage relation

$I_D = I_S\left(e^{\frac{kV_D}{T_k}} - 1\right)$

I_D = Diode Current

V_D = Voltage across Diode

where, I_S = Reverse Saturation Current

$T_k = T_C + 273^\circ$, $k = \frac{11600}{\eta}$, *η is known as ideality factor*

with $\eta = 1$ for Ge and $\eta = 2$ for Si for low levels of diode current and $\eta = 1$ for Ge and Si for higher levels of diode current.

This expression gives the current flowing in a diode when the voltage across the diode or the biased voltage is V_D. K is a constant given by 11600 by eta. Eta is known as ideality factor of diode. The value of eta is 1 for germanium and 2 for silicon when the diode current is low that is in the lower region of the diode current. These are different values but in higher level of diode current you will be having the same eta value 1 for both germanium and silicon. The diode current I_D is bearing a relationship given by this equation with the voltage. I_S is the reverse situation current which we have discussed and the Kelvin temperature T_k is given by centigrade temperature plus 273 degree. This is Kelvin; mind it, it is not centigrade. This relationship actually is helpful in finding out the characteristic of the current versus voltage applied in the diode.

If we observe the volt ampere characteristic, V-I characteristic of diode then this plot will show both under reverse bias as well as forward bias, the characteristic for two materials germanium and silicon. We will explain this plot.

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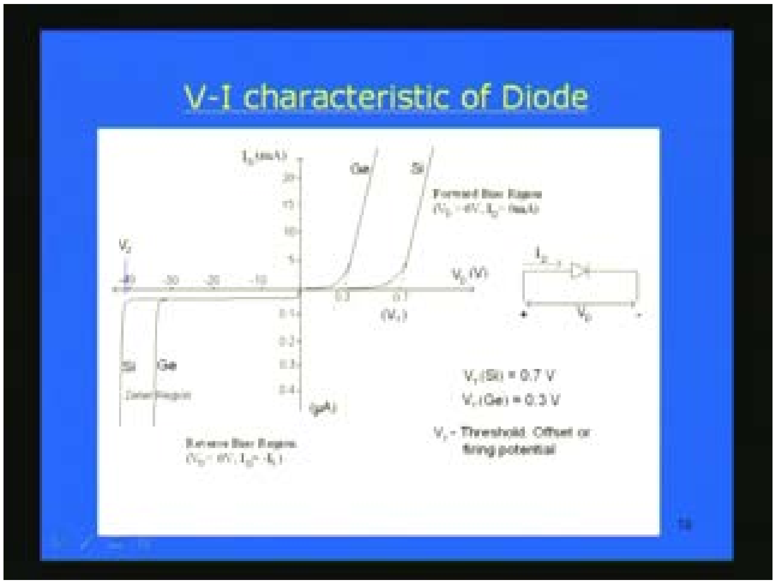

V-I characteristic of Diode

$V_T(Si) = 0.7$ V

$V_T(Ge) = 0.3$ V

V_T - Threshold, Offset or firing potential

Under forward bias condition here, this portion the threshold or offset or firing potential it is called which is nothing but the built-in potential or the potential barrier that we have discussed the values are generally taken as 0.7 volt for silicon and 0.3 volt for germanium. The voltage which is applied across this diode is V_D. That V_D must be greater than 0.3 for germanium and 0.7 for silicon in order that the current starts flowing in the diode. That means when the voltage applied across the diode is less than 0.3 volt for germanium and 0.7 volt for silicon there will be no current flow in the diode because the barrier potential is not overcome. After it is increased beyond 0.3 volt for germanium, you will find that the current rises almost exponentially. For a very small change in the applied voltage you will find a huge change in the current and this will be exponentially growing current and similarly for silicon, similar curve only that its barrier potential is 0.7 volt.

In the reverse bias condition when I apply a negative voltage that is reversed biased diode you will find that the current is very small in the order of microampere and even if you go on increasing the voltage this current which is the reverse saturation current will not increase. It will be almost constant because as I have mentioned earlier it will be dependent on the temperature. Unless and until you increase the temperature this current is not going to increase. It will be almost constant but till what point? You will find that if you go on increasing the reverse bias, a point will come when you apply a very high voltage there will be sudden rise in the current and that point is known as breakdown voltage or it is also called as Zener voltage. That phenomenon happens. The breakdown of this diode will happen because when you go on increasing the reverse bias potential for a very high potential being applied the electrons in the semiconductor will be getting a very high kinetic energy to break open from the covalent bonds, make themselves free and this will be again knocking out other electrons and this process will continue. It is like a chain process and if it continues within a very short time you will be getting an avalanche of carriers being produced. Suddenly there will be a very sharp rise of current because of this process which is known as avalanche breakdown. Because of very high kinetic energy being gained by the electrons they will be knocking out from the covalent bond.

Similarly the electrons which are knocked out will also be gaining high kinetic energy. They will knock out other covalent bond electrons. In this way it will be a cumulative process. So this avalanche breakdown takes place. Suddenly current rises to a very high value. This is also known as Zener breakdown. It is called Zener breakdown because this phenomenon is actually exploited or utilized effectively in Zener diode which we will be discussing later. That is why from that Zener name this also is known as Zener breakdown and for Zener diode basically this breakdown can occur at a smaller voltage because Zener diode is a special kind of diode. It is a very highly doped diode. When you dope it very highly the breakdown voltage will be smaller. If it is lightly doped you will find that at greater voltage this breakdown will happen.

These two regions, forward bias and the reverse bias are together described in this V-I characteristic which is a diagrammatic representation of the equation or representation or expression which we have got for diode current versus diode voltage. Because this avalanche has been taking place here we must be very careful about the voltage that we are operating under the reverse bias condition. Because this current is so high the power will be very high and the diode should be able to withstand this very high power. The power dissipation capability of the diodes will be very high and in normal diodes if we apply a very high reverse bias potential then it may not be possible for the diode to sustain that high power being dissipated. So you generally do not apply in a normal diode such a high potential and for that particularly Zener diodes are used which can withstand this high power. The power dissipation capability is more and that is why this maximum voltage beyond reaching the Zener breakdown is called peak inverse voltage and that is a very important parameter for any diode.

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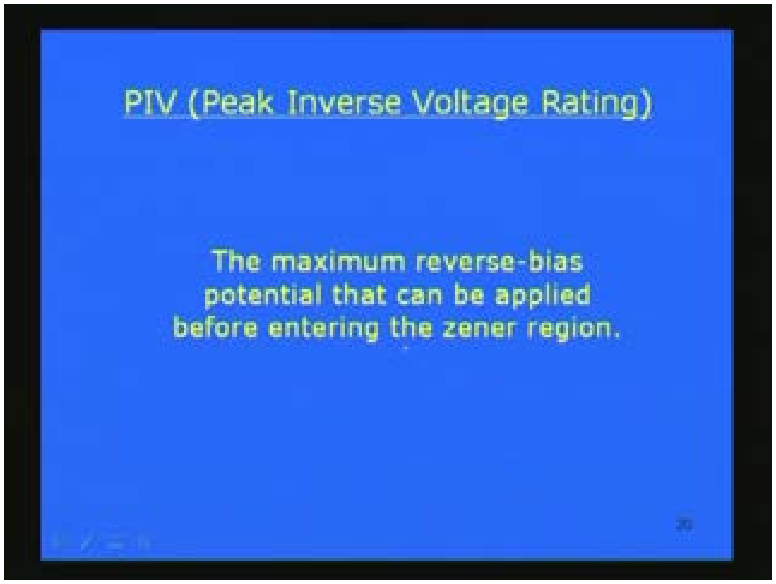

PIV (Peak Inverse Voltage Rating)

The maximum reverse-bias potential that can be applied before entering the zener region.

The maximum reverse bias potential that can be applied to the diode before entering the Zener region. PIV of a diode, that rating you have to always remember before applying it under the reverse bias condition. We will be considering a diode but before going to the practical diode let us consider a theoretical ideal diode.

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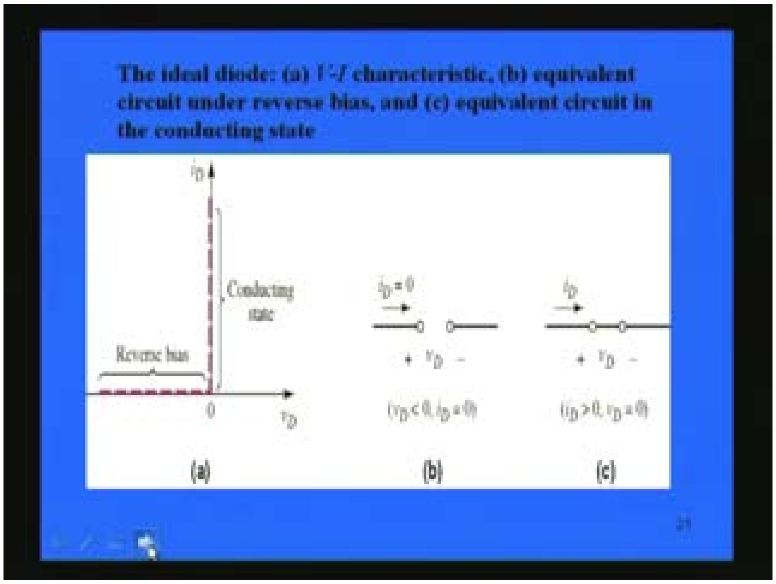

The ideal diode: (a) *V-I* characteristic, (b) equivalent circuit under reverse bias, and (c) equivalent circuit in the conducting state

Why I am calling it theoretical because practically you will never get a very ideal diode where you will be getting a V-I characteristic like this. This is a purely theoretical diode and why I am discussing this is because before going to the actual practical diode to analyze it, it is easier to take an example of a very simple diode which is ideal. Ideal in the sense that the ideal diode will not conduct that means whenever you apply a reverse bias the current is zero, totally zero. That is it is like an open circuit under reverse bias condition when V_D is less than zero then current will be zero. This is like an open circuit and whenever current is greater than zero, that means when current starts flowing the voltage drop across the diode is zero. It is like a short circuit condition. Ideal diode has this type of characteristic that it is like a switch. Under reverse bias it is like an open switch, open circuit, it is opening. Under forward bias when it conducts it's like a short circuited switch because voltage drop is zero. The ideal diode is having this type of characteristic that when it is under reverse bias, current is zero when it is conducting the voltage is zero. This is a theoretical diode which will help in further analysis. That is why we are bringing in this ideal diode.

If we consider the diode characteristic then we can find out the resistance of the diode also. The diode characteristic is V_D I_D characteristic. Then if I want to find out the resistance of the diode since it is a nonlinear character, mind it, it is not linear. The diode is linear only in the higher portion of the current region. This region we can assume to be almost linear. But practically it is not linear. If we want to find out the resistance of the diode at the point where it is being operated, at the voltage which is being applied suppose this voltage and at that voltage this is the current. Q is the point where we are operating the diode. Then the resistance which is known as DC resistance or static resistance is V_D by I_D. That is this voltage by this current will give you the DC or static resistance. But if you apply a variable voltage like a sinusoidal voltage then we will have to find out the dynamic resistance.

How to find out the dynamic resistance? What you do is that you draw a tangent at that point where you are operating the diode and at the two points you find out the difference in voltage and difference in current. That is dynamic resistance will be given by del V_D by del I_D. That is called dynamic resistance or AC resistance because you are operating the diode and there is signal which will be bringing the current to this point and voltage to this point as well as this point because it is a sinusoidal type of voltage or varying voltage. Then we have to find the dynamic resistance of this diode.

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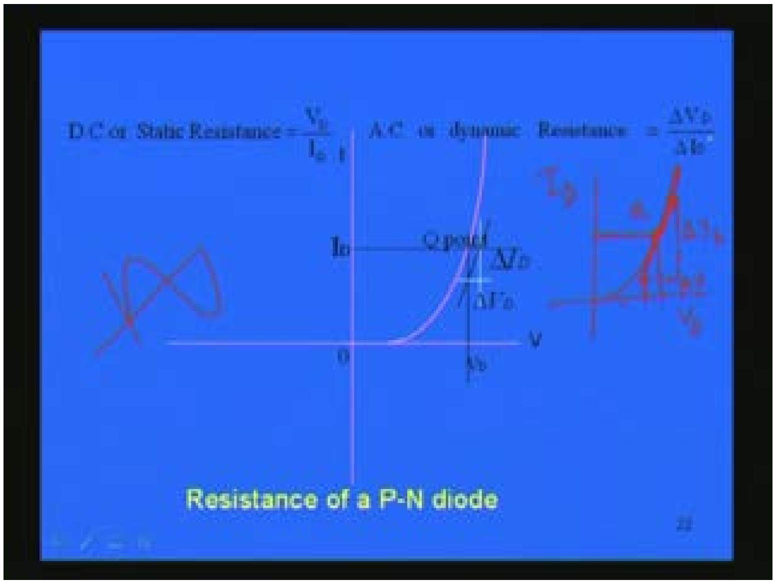

D.C or Static Resistance = $\frac{V_D}{I_D}$ A.C or dynamic Resistance = $\frac{\Delta V_D}{\Delta I_D}$

Resistance of a P-N diode

Another important factor for finding out the diode current is the temperature effect because as we have mentioned the temperature is affecting the minority carriers. That means reverse saturation current will be affected when you have a varying temperature. That means suppose we have now increased the temperature what will happen to this reverse saturation current?

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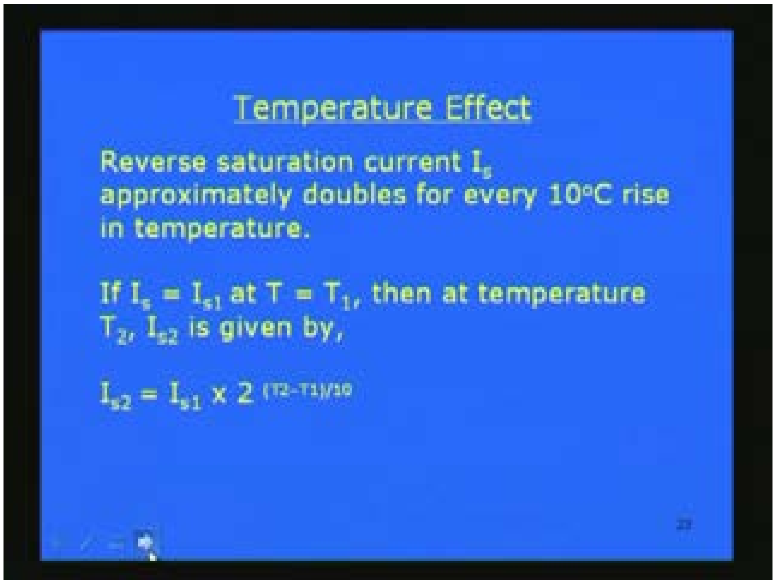

Temperature Effect

Reverse saturation current I_s approximately doubles for every 10°C rise in temperature.

If $I_s = I_{s1}$ at $T = T_1$, then at temperature T_2, I_{s2} is given by,

$I_{s2} = I_{s1} \times 2^{(T2-T1)/10}$

It will be increasing. How much it increases that is actually given by a law that for every 10 degree centigrade rise in temperature the reverse saturation current approximately doubles. That means if suppose at temperature T_1 we have a current I_{s1}, reverse saturation current and at temperature T_2 I_{s2}, the reverse saturation current will be equal to I_{s1} multiplied by 2 to the power T_2 minus T_1 by 10 because for every 10 degree centigrade it doubles. So it will be power of 2 by that factor by which it is increased divided by 10. This will have to be counted when you have a variation in the temperature.

Let us now find out the resistance of the diode. The diode resistance can be found out from the V-I characteristic which we have just now seen and from that V-I characteristic by finding out the ratio between the voltage and current at the particular operating point where you are operating the diode it can be found out. Let us find out the diode resistance. We have the V-I characteristic of this diode as this type of characteristic curve where this is the voltage across the diode and current through the diode. This is a non-linear characteristic. In order to find out the resistance we have to do it at a particular point where you are operating the diode. Suppose I have voltage applied across the diode and the current through the diode given by a particular point Q then you will be finding out the resistance which is known as static resistance or it is also known a DC resistance; static resistance or DC resistance. Static resistance is given by the ratio between the voltage and current at that particular point Q where you are operating. But when you have a signal being given to the diode like a sinusoidal voltage suppose I am applying in the diode then as you can see that this voltage signal it is going from a very high peak value to a lesser value.

If we apply a varying AC signal then we have to find out the dynamic resistance. In order to find out the dynamic resistance you draw a tangent at this point where you are operating the diode and you want to find out the dynamic resistance. Then at the 2 points on the tangent you find out the incremental change of the current and change of voltage. This will be del V_D and del I_D.

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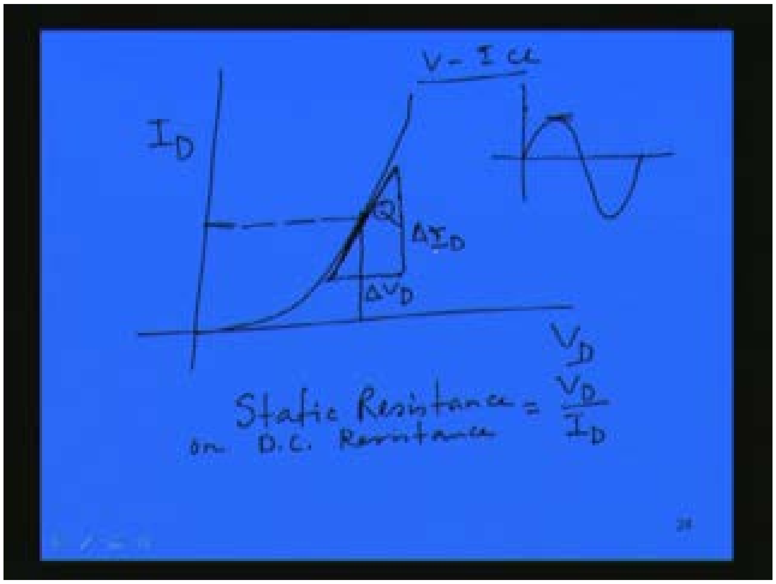

Static Resistance $= \frac{V_D}{I_D}$
or D.C. Resistance

The dynamic resistance or AC resistance is given by del VD by del ID around this Q point that is incremental change in voltage by incremental change in current.

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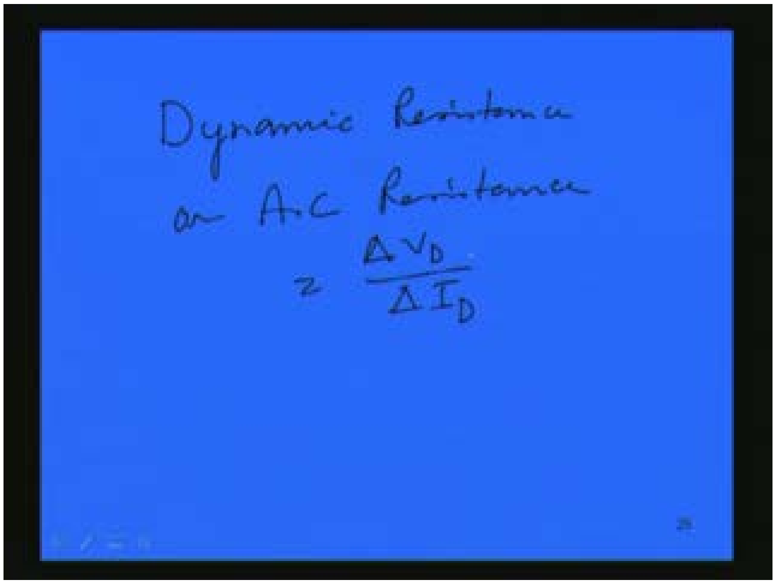

Dynamic Resistance
or A.C Resistance

$$= \frac{\Delta V_D}{\Delta I_D}$$

Let us do one example with all these expressions that we have studied till now which is about a germanium diode. A germanium diode displays a forward voltage of 0.25 volt at 10 milliampere current at room temperature which is 300 degree Kelvin. Standard room temperature is taken at 300 degree Kelvin. For this example you have to find the reverse saturation current. That is I_S you have to find out.

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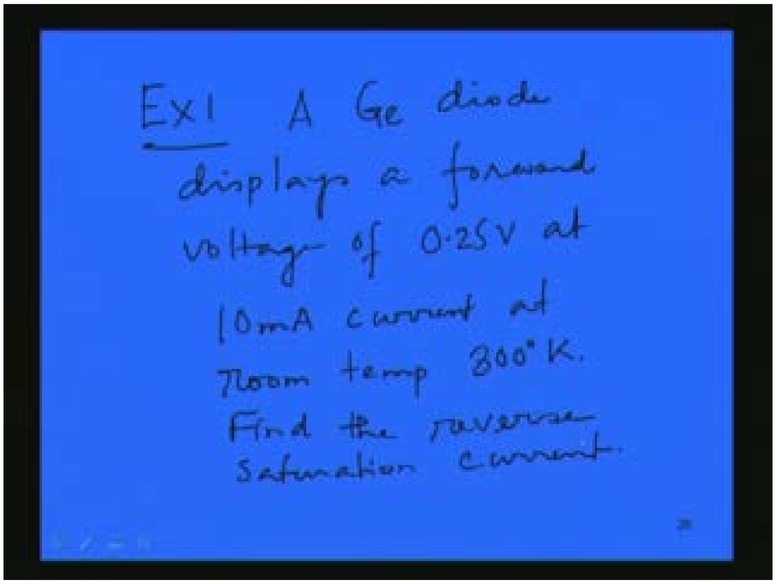

Ex 1 A Ge diode
displays a forward
voltage of 0.25V at
10mA current at
room temp 300° K.
Find the reverse
saturation current.

Here you have to assume that diode ideality factor eta is 1. This is given to you. Also you have to calculate the bias voltage needed for diode current of 1 milliampere. What will be the bias voltage to be applied when the diode current is 1 milliampere and also 100 milliampere? These three cases; it is given at 10 milli ampere. Then you have to find out for 1 milliampere and 100 milliampere at the same temperature. Temperature does not change. This is the second part of the problem.

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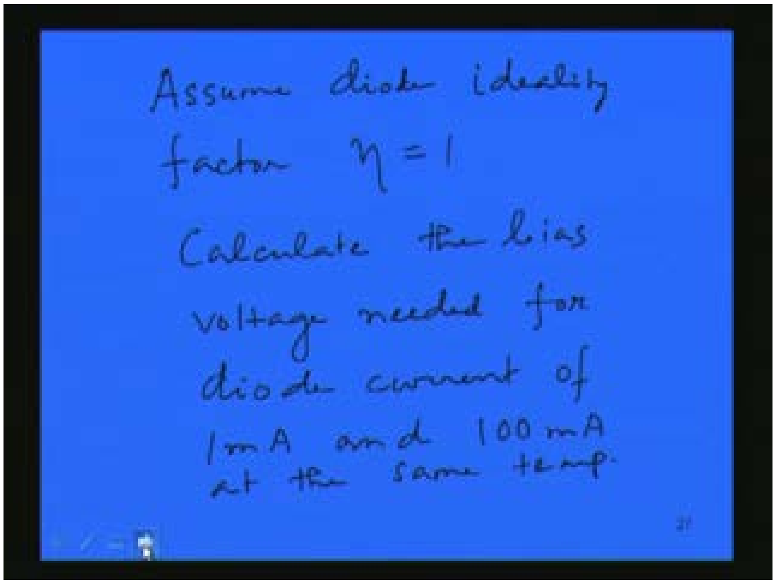

Assume diode ideality factor $\eta = 1$

Calculate the bias voltage needed for diode current of 1mA and 100mA at the same temp.

Also you have to estimate the value of the reverse saturation current I_S and also forward current at 0.25 volt at 30 degree centigrade above room temperature. Now the temperature is increased. At the new temperature you have to find out the value of the reverse saturation current as well as the forward current. To solve this example we will be taking that expression for diode current which is I_D equal to I_S into exponential KV_D by T_K minus 1. This is the key equation which we have to use. In the first part of the problem it is given that it is germanium and it is having a forward voltage of 0.25. So V_D is equal to 0.25 volt and the current which is flowing, I_D is 10 milliampere. Bring it to the ampere scale 10 into 10 to the power -3 ampere. I am bringing it to volt-ampere scale so that there is no mistake between milliampere and volt scale to have a conformity and temperature is mentioned. It is given in Kelvin. T_K is equal 300 degree Kelvin which is given. In this equation we have to find out this K. K is equal to 11600 by eta. Eta is given. Ideality factor is given to be 1. It is simple; 11600 by 1 becomes 11600. K we have found out. Anything else? No.

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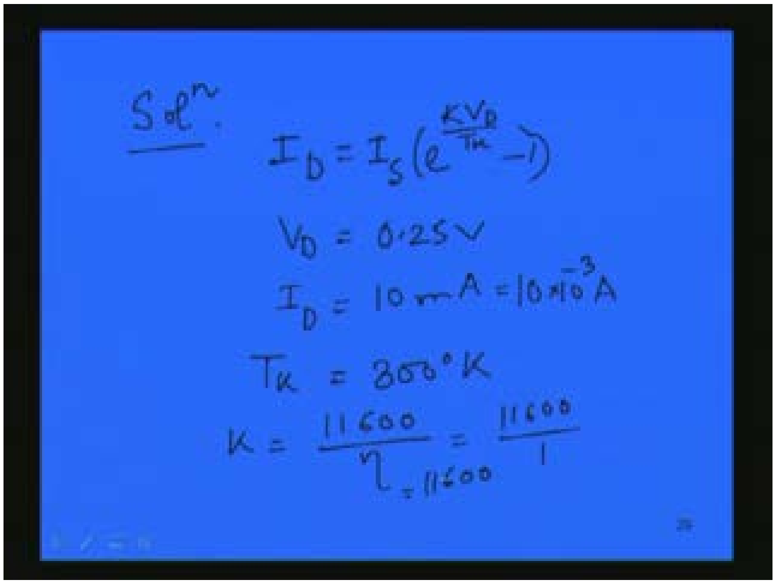

Sol^n:

$$I_D = I_S\left(e^{\frac{KV_D}{T_K}} - 1\right)$$

$$V_D = 0.25\,V$$

$$I_D = 10\,mA = 10\times10^{-3}\,A$$

$$T_K = 300^\circ K$$

$$K = \frac{11600}{\eta} = \frac{11600}{1}$$

$= 11600$

We can now proceed to find out the current. In the current expression we can now replace 10 milliampere means 10 into 10 to the power of -3 ampere is equal to I_S into exponential to the power K is 11600 into 0.25 is the bias voltage divided by T_K; kelvin temperature is 300 which is given minus 1. This equation if you simplify 10 to the power -2 is equal to I_S you have to calculate this part; e to the power this whole term will be finally 15782.65 minus 1. We can find out what is I_S? I_S will be equal to 6.34 into 10 to the power -7 amperes. This is the reverse saturation current flowing or it is 0.634 microampere current is flowing.

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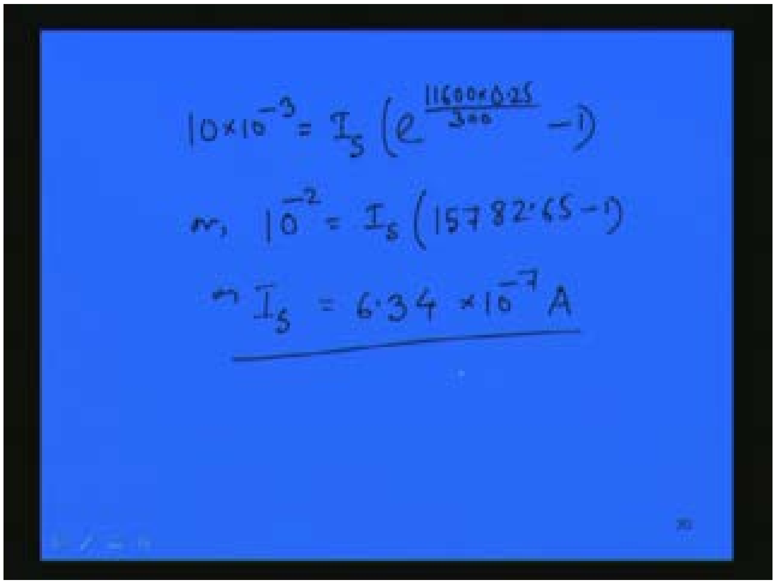

$$10\times10^{-3} = I_S\left(e^{\frac{11600\times0.25}{300}} - 1\right)$$

or, $10^{-2} = I_S\,(15782.65 - 1)$

or $\underline{I_S = 6.34\times10^{-7}\,A}$

Next part of the problem is when 1 milliampere diode current is flowing. For 1 milliampere diode current we have to now again write this equation I_D equal to I_s into e to the power KV_D by T_K minus 1. This equation we are using again but now what is given is that I_D is given as 1 milliampere. So 1 into 10 to the power -3 bringing it to ampere scale and this reverse saturation current is not changing because there is no change of current. That reverse saturation current which we have just now found out that is equal to 6.34 into 10 to the power -7; that will be same and exponential to the power 11600 that is also same into voltage is now 0.25 volt, V_D. The second part you have to find out bias voltage. V_D is not given. V_D you have to find out and T_K is not changing 300 minus 1 and we have to find out the bias voltage or what is applied? In this example we need to simplify. Simplification gives 1 into 10 to the power -3 equal to 6.34 into 10 to the power -7. This part you have to calculate. This whole part you have to now keep it as it is. That is 11600 V_D by 300 minus 1 from here we have to find out V_D. This calculation is giving the value of 38.67. This value is 38.67; e to the power 38.67 V_D minus 1. This part is separate; equal to 1 into 10 to the power -3 by this whole term 6.34 into 10 to the power -7. This V_D we have to find out. You have to use natural logarithm for it.

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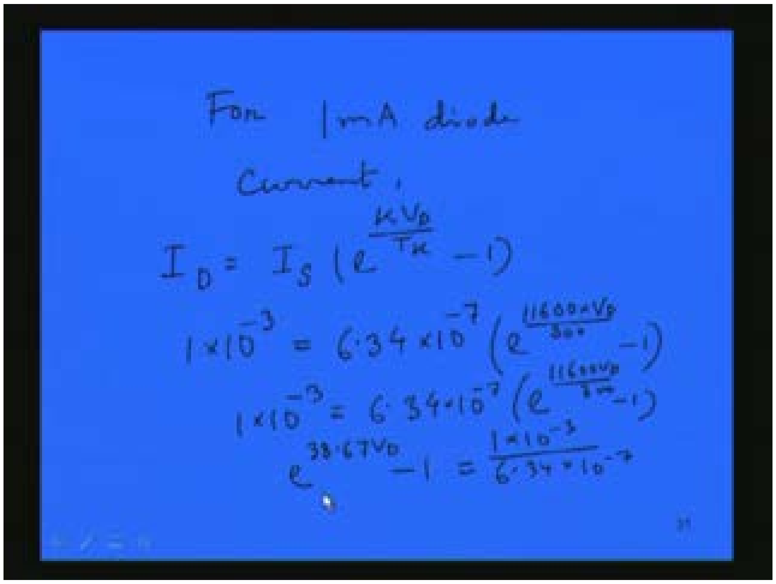

For 1mA diode Current,

$$I_D = I_S\left(e^{\frac{KV_D}{T_K}} - 1\right)$$

$$1\times10^{-3} = 6.34\times10^{-7}\left(e^{\frac{11600\times V_D}{300}} - 1\right)$$

$$1\times10^{-3} = 6.34\times10^{-7}\left(e^{\frac{11600\times V_D}{300}} - 1\right)$$

$$e^{38.67V_D} - 1 = \frac{1\times10^{-3}}{6.34\times10^{-7}}$$

e to the power 38.67 V_D will be equal to 1 plus 0.1577 into 10 to the power 4. We can now find out right side which is equal to 1578. That is e to the power 38.67 V_D equal to this. We can find out 38.67 V_D equal to natural logarithm of 1578 and that is equal to 7.3639. We can find out what is V_D? Applied voltage or bias voltage is divide this by this it will be equal to 0.19 volt. For this 1 milliampere diode current, we have to apply 0.19 volt.

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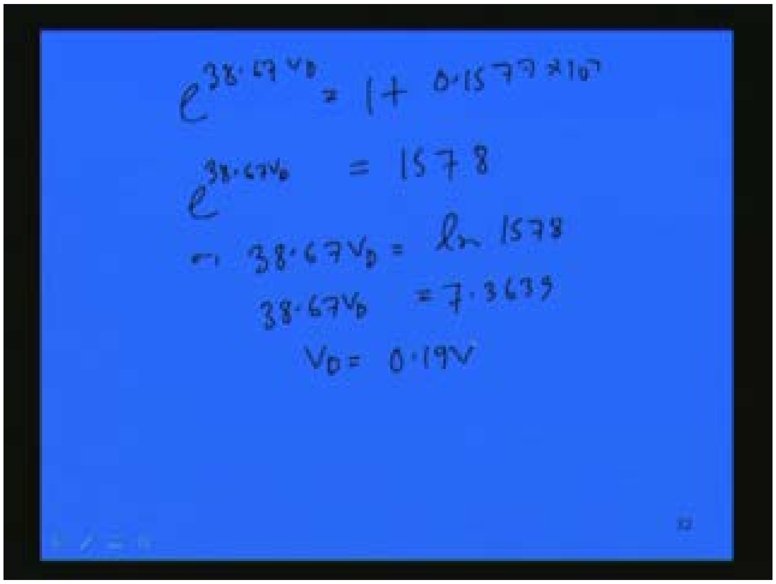

$$e^{38.67 V_D} = 1 + 0.1577 \times 10^{4}$$

$$e^{38.67 V_D} = 1578$$

$$\Rightarrow 38.67 V_D = \ln 1578$$

$$38.67 V_D = 7.3639$$

$$V_D = 0.19 V$$

For the other part when the diode current is 100 milliampere similar expression I use I_D equal to I_s into e to the power KV_D by T_K minus 1. Putting this value of I_D here which is 100 milliampere then we get 100 into 10 to the power -3 ampere; same as reverse saturation current 6.34 into 10 to the power -7 and e to the power 11600, V_D we do not know by 300 minus 1. It will be equal to e to the power again similarly proceeding we will get e to the power 38.67 V_D minus 1. The other side it will be equal to 100 into 10 to the power -3 by 6.34 into 10 to the power -7 and that will be equal to this value comes out 15.77 into 10 to the power 4. This is equal to e to the power of 38.67 V_D minus 1 equal to this value. We get e to the power 38.67 V_D equal to 157701.

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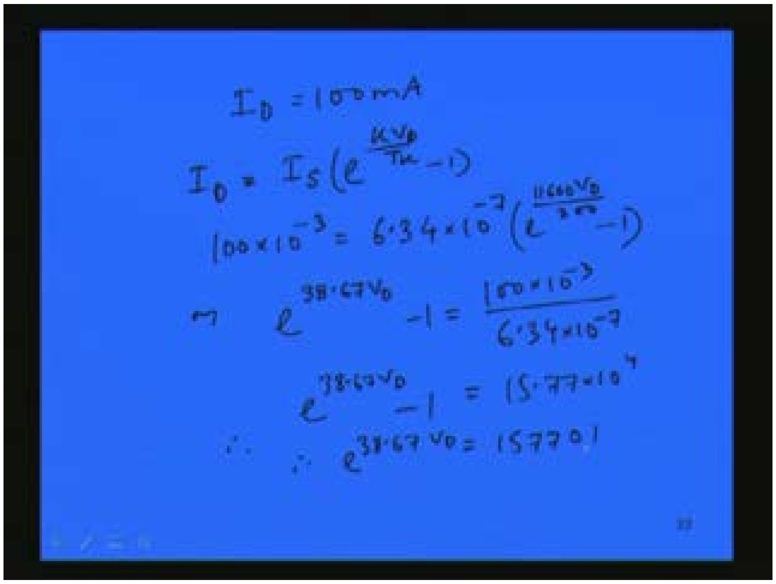

$$I_D = 100 mA$$

$$I_D = I_S \left(e^{\frac{KV_D}{T_K}} - 1 \right)$$

$$100 \times 10^{-3} = 6.34 \times 10^{-7} \left(e^{\frac{11600 V_D}{300}} - 1 \right)$$

$$\Rightarrow e^{38.67 V_D} - 1 = \frac{100 \times 10^{-3}}{6.34 \times 10^{-7}}$$

$$e^{38.67 V_D} - 1 = 15.77 \times 10^{4}$$

$$\therefore \quad \therefore \; e^{38.67 V_D} = 157701$$

From here 38.67 V_D you take out by taking natural logarithm of 157701. That is equal to 11.97. V_D, the bias voltage which has to be applied to get 100 milliampere current becomes 11.97 divided by 38.67 which come out to be 0.3095 volt. This much of voltage is required. Notice that we are getting 0.3095 in this. For this 0.3095 voltage, 100 milliampere but for 1 milliampere we had to apply a voltage of 0.19 volt.

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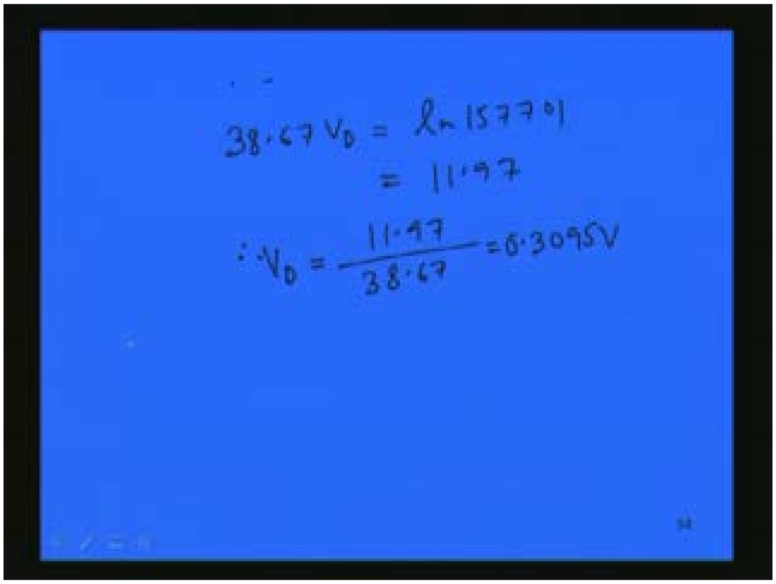

$$38{\cdot}67\,V_D = \ln 157701$$
$$= 11{\cdot}97$$
$$\therefore V_D = \frac{11{\cdot}97}{38{\cdot}67} = 0{\cdot}3095\,\text{V}$$

Even if we increase the voltage by less than twice, we are getting 100 times of diode current. For a small change of applied voltage we are getting such a huge current change or rise and that is very, very clear from that characteristic curve also.

In the third part of the problem temperature is raised by 30 degree centigrade from room temperature. Earlier it was at room temperature now it has been raised by 30 degree centigrade. What will happen is the reverse saturation current will be now rising and you know that for each 10 degree centigrade rise the reverse saturation current rises by 2 times. Earlier it was 6.34 into 10 to the power -7. That will be now increased by a factor 2 to the power 30 by 10. That means 2 the power 8 times it will be increasing. So 8 times of this 6.34 into 10 to the power of -7 becomes 50.72 into 10 to the power -7 ampere is the new reverse saturation current.

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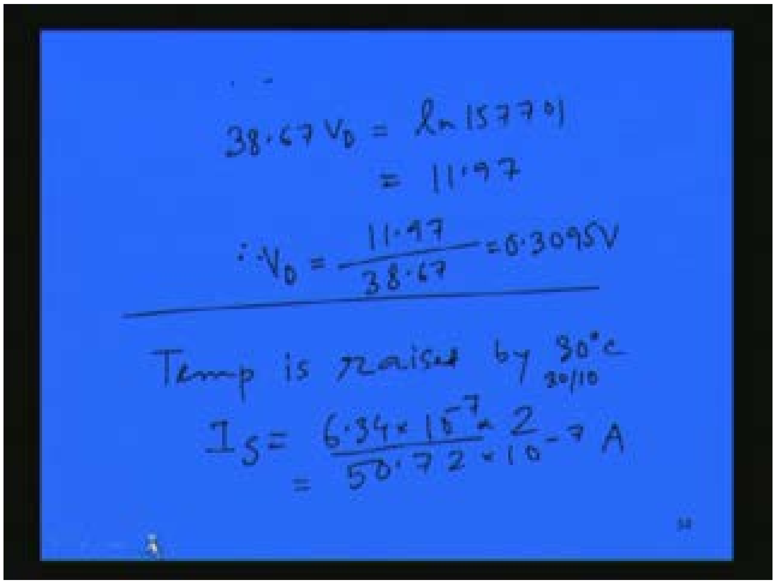

$$38.67\,V_D = \ln 157701$$
$$= 11.97$$
$$\therefore V_D = \frac{11.97}{38.67} = 0.3095\,V$$

Temp is raised by 30°c
30/10

$$I_S = 6.34 \times 10^{-7} \times 2$$
$$= 50.72 \times 10^{-7}\,A$$

When the reverse saturation current is increased the total current will also change. The new Kelvin temperature is 330 degree Kelvin. Earlier it was 300 now it is changed by 30 degree. 330 degrees Kelvin is the new temperature. Total diode current for this new temperature will become I_D equal to 50.72 into 10 to the power -7 into exponential 11600 into 0.25 because voltage which is applied is 0.25 volt it has been mentioned and this Kelvin temperature is changing to 330 minus 1. This right side if you compute it comes to 10 to the power -7 into this part. This part will be equal to 6553.31; this whole term becomes this. Computing this value we get 332384.1 into 10 to the power -7. To write it in the milliampere order it will be 33.24. Because if you consider in milliampere 10 to the power -3 you keep; then 10 to the power -4 when you multiply that will be 33.24 milliampere which is the answer. You can see the change in the diode current when you raise the temperature by 30 degree centigrade. Earlier the diode current was 10 milliampere. Now it has become 33.24 milliampere because of the rise of the temperature. We have not changed the biasing voltage. Only rising the temperature by 30 degrees centigrade has resulted in rise of the diode current to 33.24 milliampere from 10 milliampere.

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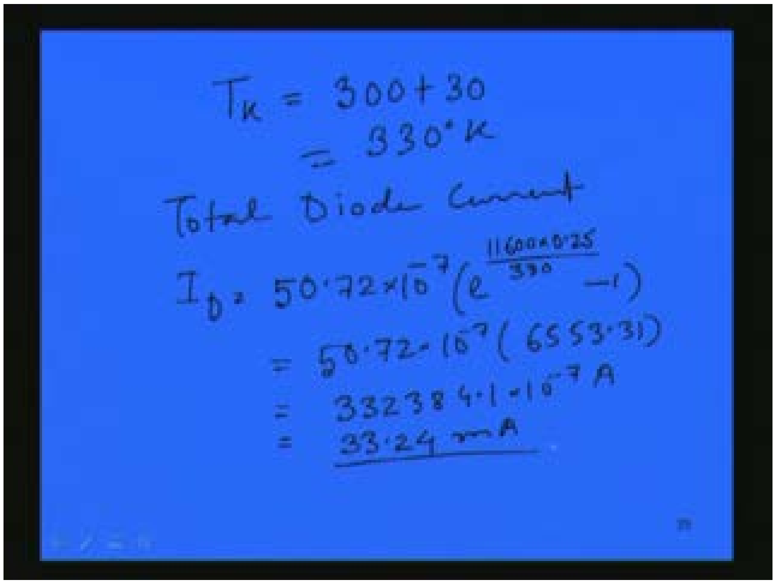

$T_K = 300 + 30$

$= 330°K$

Total Diode Current

$$I_D = 50 \cdot 72 \times 10^{-7} \left(e^{\frac{11600 \times 0 \cdot 25}{330}} - 1 \right)$$

$$= 50 \cdot 72 \times 10^{-7} (6553 \cdot 31)$$

$$= 332384 \cdot 1 \times 10^{-7} \text{ A}$$

$$= \underline{33 \cdot 24 \text{ mA}}$$

We have seen the effect of temperature change on the diode current.