Semiconductor Device Modelling and Simulation
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Lecture - 16
P-N Junction

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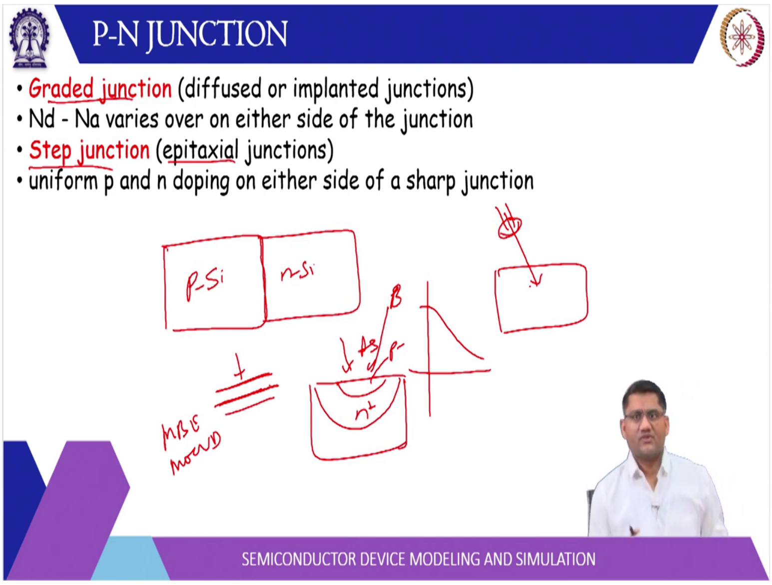

Hello students welcome to lecture number 16. Today we will discuss about the P-N Junction. So, in this lecture we will discuss how the P-N Junction in equilibrium. Now P-N Junction is basically is made up of P type material and N-type material. So, P tap semiconductor lesser silicon and N-type semiconductor. Now this interface or called metallic metallurgical Junction it can be a step Junction right and such Junctions are fabricated using epitaxial processes.

So, epitaxial processes include like molecular beam epitaxy MBE, MOCBD. So, these are Atomic layer deposition techniques or epitaxy processes. So, where the material properties are such that they abruptly change from one Atomic layer to another Atomic layer other possible Junctions are the graded Junctions. So, graded Junctions are basically designed or fabricated using diffusion techniques or implantation techniques.

So, diffusion is basically let us say you have this piece of semiconductor then you diffuse let us say arsenic impurity into it, it becomes N type then you on top of this again you diffuse some P type impurity let us say boron then this becomes P type. So, the profile in case of diffusion they are not abrupt they are graded basically because these diffusion profiles Zenerly have some curve like this or they can be obtained using implantation.

Implantation is another fabrication technique where using us source energetic ions are actually injected into the material and the material is any later on some heat treatment is given so, that these impurities redistribute themselves to latticeites. So, there is another process by which we get the graded Junction.

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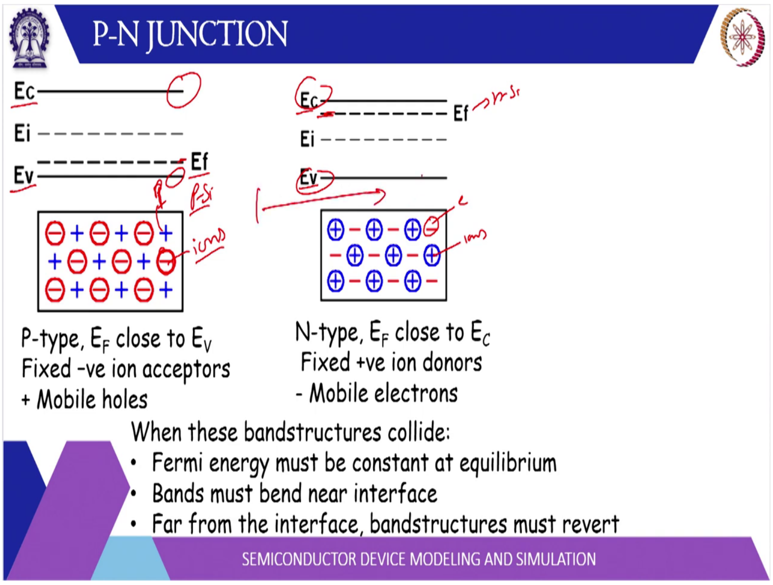

Now step Junction is a simpler case. So, we will use this case to understand how the P-N junction actually works. So, here you can look at the band diagram of a semiconductor. So, you have a balance band here then conduction went here and the Fermi level is here that means it is a P type semiconductors on right side we have another material valancement conduction band and Fermi level is here it means it is N-type semiconductor. So, in P type semiconductor the Fermi level is close to the valance bandage and the P type semiconductor is achieved by the impurities which give a hole or that means they take away electron that means there is a negative charge ions and these are positive holes which are mobile.

So, there are 2 types of charges immobile charges called ions and mobile charges called carriers or holes in case of P type. In case of N times N type semiconductor immobile charges are again positive ions and mobile charges are electrons. Now when these 2 pieces of semiconductor they come together what will happen at least in case of equilibrium the Fermi energy should align at the interface.

So, if the Fermi energy has to align then these bands conduction band and valance band they will have to adjust themselves. So, they will go under some kind of bend bending. And of course if you move away from the interface it should revert back to the original configuration.

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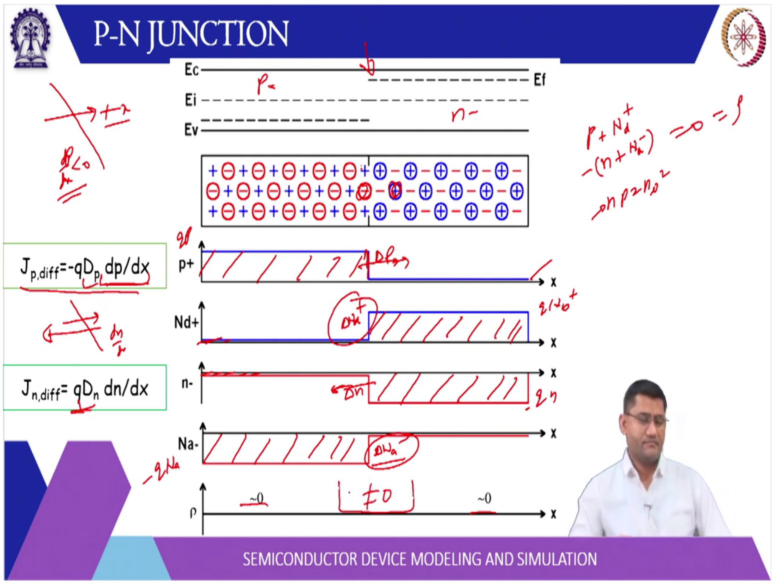

So, here you can see P type semiconductor N-type semiconductor. Now here we have shown the comparative band diagram and the charges without actually connecting them. So, they are still separate but the band diagrams are shown side by side. Similarly you can see these positive ions are immobile these negative ions are immobile and then these holes and these electrons are mobile. So, if you look at the charges.

So, individually there should be charge neutral. So, total charge is number of holes which is positive charge plus if there are some positive ions. So, that is donor ions minus negative charges that are electrons plus acceptor ions and that should be zero. So, on P side we have acceptor ions and holes. So, this is the holes which is non zero and acceptance which is also non zero. So, the charge is basically q times N a with a negative charge it is q times P with a positive charge and there are no donor ions here.

So, this is zero and correspondingly how electrons are very small in number because by law of mass is N n P product is N i square and it is individually true in each of the semiconductors. Similarly in the case of N-type semiconductor there should be electrons. So, this is q times N electron a negative charge. So, minus q times N and corresponding donor ions that is q times Nd Plus and of course number of holes will be very small because they follow this law of mass XR N P is N i Square and because there are no accept price. So, it is again also zero.

So, individually total charge this is basically rho. So, it is individually zero for both the cases. Now if you notice here there is a certain change in the carrier concentration. So, there is a certain changes hold concentration there is a certain change in donor ions there is certain change in electron concentration there is certain change in certain lines but these are immobile. So, they cannot move.

So, only particles that can move are the holes and the electrons. So, hole will move they will have tendency to move from high concentration to low concentration that means holes will move from left side to the right side. Similarly electron will move from right side to left side and this process is called diffusion because they are diffusing from high concentration to low concentration there is no applied field as such which is causing them to move.

It is just pure concentration gradient that is causing them to move and therefore they will constitute some kind of diffusion current and that diffusion current is given by some q times d P times dp by dx where dp by dx is the whole concentration gradient it has a negative sign because if you look at the whole concentration they if the gradient is negative. So, this is gradient negative. So, if gradient is negative that is less than zero then this hole will move in x direction. So, current will have the negative sign because it is in positive x direction and dp by dx is negative.

Similarly in case of electrons if dn by dx is negative then electron will move in positive x direction but due to that current will be negative x direction. So, you do not have a negative sign here is q times dn by dx and capital DN in small dpare the diffusion coefficients. So, only the electron and holes will move and these ions which are donor ions and acceptor ions which are fixed charges they will not move.

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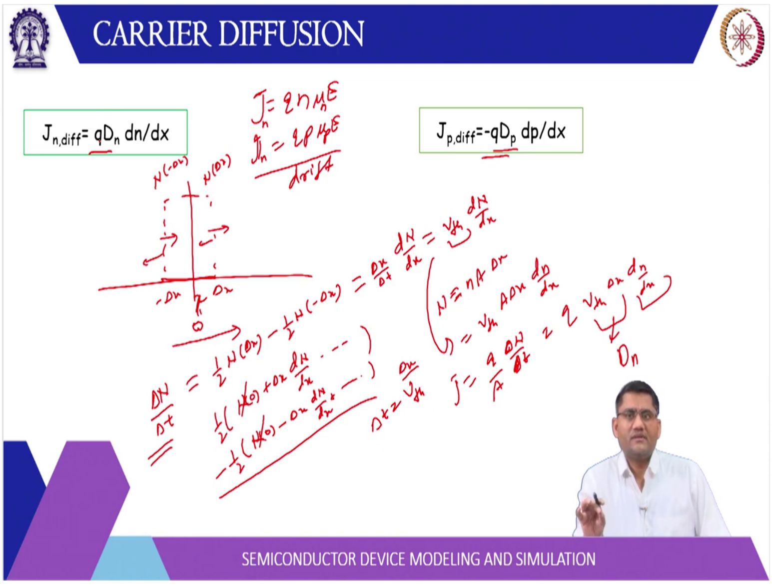

So, when these mobile charges will move then the charge may not be zero in the vicinity of interface. So, let us look at the diffusion current we already know that we have discussed the drift current. So, drift current is given by q times N times V or is given by mu times electric field and this is for electron similarly for holes drift current is q times P times mu times E. So, this is Mu P this is Mu N where mu is the mobility and that concept we have already discussed.

So, there are 2 currents mechanism so, far we have learned one is the drift current other is the diffusion current. Now diffusion current you can understand like this let us say we consider a one dimensional piece of semiconductors and let us say at position x we consider a small section plus Delta x and minus Delta x l i say x equal to zero. So, here the concentration is N times minus Delta x here the concentration is N at plus Delta x.

So, if you consider 1D situation then half of them will move to the right and half of them will move to the left. So, if we calculate the net movement towards the right that is basically half N at Delta x minus half N at minus Delta x. So, this if you use Taylor series expansion you can write N at Delta x basically N at zero plus Delta x times dN by dx and so on other hydro terms minus half similarly N at zero.

Now this is minus Delta x. So, it will be minus Delta x times dn by dx and so on and then if you add these 2 terms this N 0 N 0 will cancel. So, this actually can be represented as Delta x times dN by dx. So, this is the net movement of the carriers this is basically let us say we call it Delta N the number of carriers that are crossing this small box here and if you see this one if you divide by delta t you will get some kind of flow and this delta t basically you can write in terms of thermal velocity.

So, delta t can be written as V thermal times Delta x divided by V thermal that will be delta t. So, this can be written as again V thermal times dN by dx. So, this is basically flow is related to the thermal velocity. And then you can see this N is basically total number of electron in this region and that can be related to some kind of the carrier density which is small N times the area of in area of the cross section times this small Delta x.

You can write like this if you be strict it can be take 2 Delta x also. So, this term can again be written as V thermal times a times Delta x times dN by dx. So, if you convert that into current density. So, J will be q times Delta N by delta t divided by area. So, that will be something like q times V thermal times Delta x dN by dx. So, you see that J is proportional to dN by dx and this constant V thermal times Delta x can be you know represent by some constant called the diffusion coefficient.

So, similarly we can get the expression for the whole diffusion. Now in this case the sign will be negative because that diffusion will be from high concentration to low concentration and corresponding to current flow will also be from high concentration to low concentration per whole and otherwise for the electron. So, due to that concentration grade negative sign will come here. So, later we will learn that in certain situation this dN is also related to the mobility.

Because essentially they are both of them are related to the thermal motion of the carriers in the semiconductor at a given temperature. So, our current understanding is that the current conduction there are 2 possible mechanism one is the drift or there is a diffusion. Drift requires the electric field and diffusion requires the concentration gradient at a given temperature these both will contribute to other conduction of the current.

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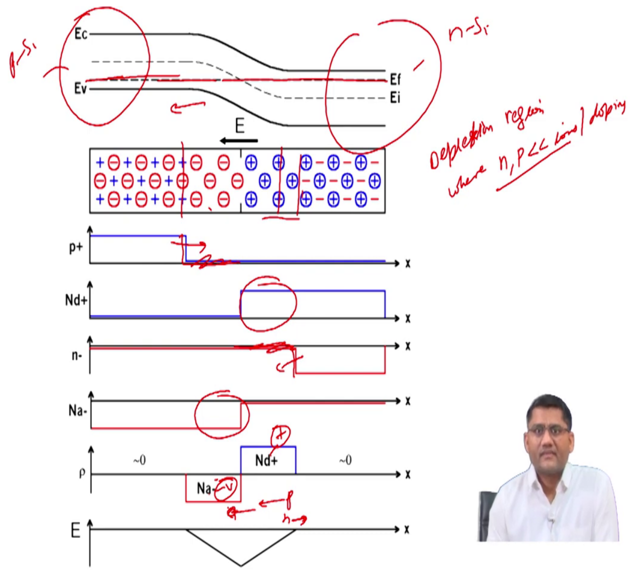

Now when we combine them the Fermi level has to be constant at equilibrium because we have not applied any bias and this also means that current flow has to be zero. Then accordingly the conduction when valence band they are bending near the interface and away from the interface you see it is again like undisturbed P type semiconductor. Here it is again undisturbed N-type semiconductor and because of this movement of carrier so, wholesale moved from here.

So, this region is depleted of holes similarly like electrons have moved from this region. So, this region is depleted of electrons. So, there are no electrons here there are no holes here. So, what is remaining there is the acceptor ions and the donor ions. So, these fixed charges are remaining here but there are no mobile ions and we call this one as a depletion region. So, by definition depletion region is a reason.

So, depletion region where number of carriers electron iron hole they are much less than these ions there or the doping there basically. So, if you apply the charge utility condition there. So, this region is no longer charge neutral. So, here will have net negative charge and this region will have net positive charge. Now if you notice one thing here because of this positive charge and negative charge a field will be set up and whose direction will be from positive charge to negative charge.

So, that field will be in minus x direction that means it will pull the holes in minus x direction it will pull the electrons in plus x direction and that flow is opposite to the flow due to the diffusion you see the holes are diffusing from left to right in plus s direction due to the field they are pulled in negative x direction. So, these 2 factors are opposing each other similarly due to concentration gradient electrons are moving from right to left but due to the developed field electrons will be attracted from left to right.

So, these 2 factors will oppose each other and in equilibrium they will essentially be equal. So, that means electron drift is equal to electron diffusion and whole drift current is equal to hole diffusion current and because this direction of the field is negative. So, this E field is basically represented by a curve here with a magnitude negative. So, it simply means the field is in minus x direction.

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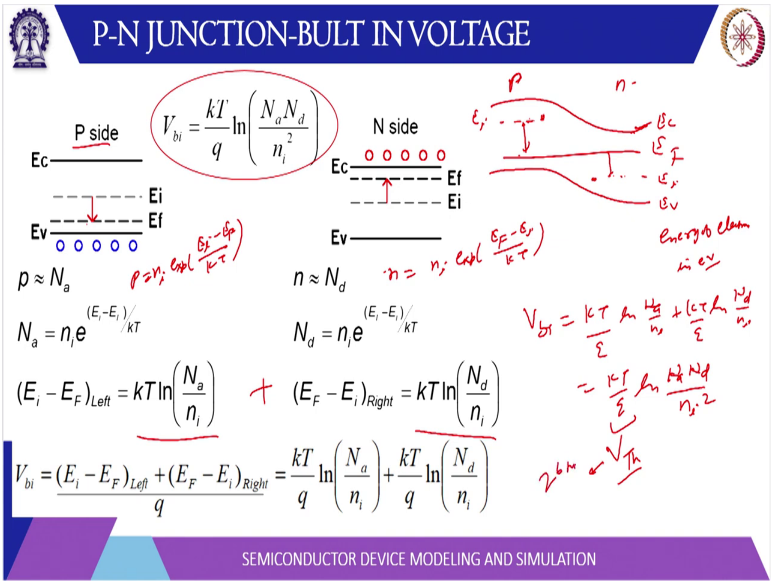

Now let us have a further look at the Venn diagram of P-N Junction because in equilibrium these Fermi levels align basically. So, that means initially on the P side permeable is below the intrinsic level by an amount called kT log N a by N i that you can easily find out from this expression for the carry concentration that P is equal to N i exponential E i minus E F by kT and similarly N is equal to N i exponential E F minus E i by kT.

So, in case of P type doping P is equal to N a. So, if you substitute here you will get this expression similarly on the N side E F is above E i by amount kT log and d by N i. Now when this Fermi level align with each other so, you can look like this, this is Fermi level and in case of N site E i is here in case of P side E i is here and the bands are basically bending like this. So, these E i are separated by an amount E F minus E i on P side and E f minus E i on N side and their magnitude actually add up.

So, this will be the overall potential difference. Now these bands if you see these are nothing but the electron energies. So, E c and E v these are the bands which actually represents the energy of electron energy of electron in electron volt. So, if you take this difference and divide by E you will get the potential difference. So, the difference between these 2 intrinsic energy levels will be the sum of these 2 factors.

So, that is basically also called V bi or built in potential. So, V bi is nothing but the sum of these 2. So, kT log of N a by N i plus kT log of N d by N i. So, this is basically energy. So, it should be q times V bi right. So, it has to be divided by Q. So, you have divided by q here and when you add these 2. So, log inside the terms inside the log they will be multiplied. So, it you will have kT by q log of N a N d by N i Square.

So, taking KT by q common now kT by q is also called thermal voltage V th and at room temperature its value is around 26 Milli electron volt. So, for P-N Junction with N a and N d doping your built-in potential is given by kT by q log N a and d by N i Square.

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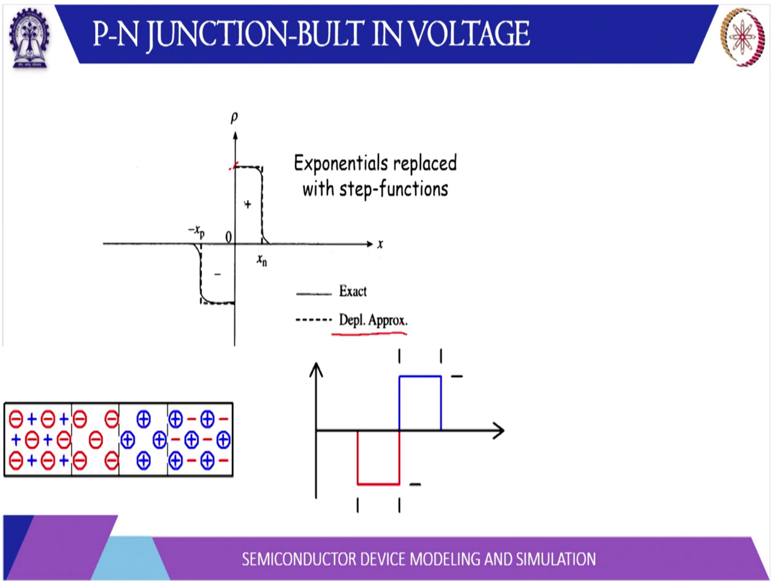

We can find other parameters also, now just to remind that we are assuming step Junction profile. So, we are basically assuming the depletion box with a abrupt transition but in reality it will not be abrupt it will have some curvature so that we will discuss in one of the problem. But right now we will move ahead with this depletion approximation. So, by solving the exact equation is also possible to find out the exact profile.

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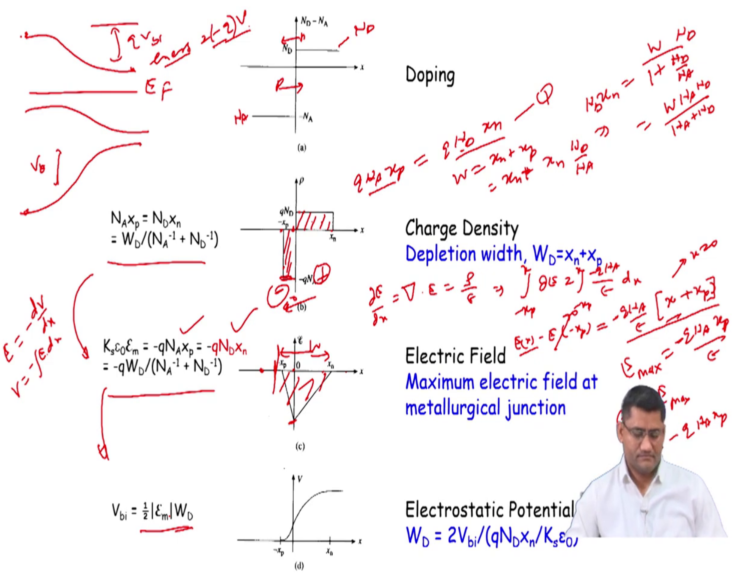

So, going ahead with the depletion approximation let us calculate other quantities. So, this is basically the doping. So, N d on the electron side or N type site and N a is on the whole side or P type side. Now because of the movement of the carriers holes, so, the holes had moved from right to left electrons are moved from N type to P type and that has basically uncovered these negative ions receptor lines and these donor ions.

Now because overall it has to be charged neutral so, these 2 charges have to be equal. So, if the width of the depletion region is zero to x P or minus x P on this P side and 0 to x N on the N side then q N a is the charge density of these ions on the receptor side multiplied by the length x P should be equal to q times N d which is a charge density on N type side multiplied by x n. So, you can remove the queue.

So, you can say N a x P is equal to N d times x n. Now total depletion width is basically sum of these 2 x and plus x p. So, if you substitute here let us say this is x N plus x P can be written in terms of x N using this equation one. So, your x P is basically x n times N d by N a. So, that gives you another expression for x n. So, that x n is equal to W divided by one plus N d by N a. So, if you again multiply just x n by N d.

So, you can write N d here. So, this simplifies to W Times N a N d divided by N a + N d or you can write in denominator 1 by N a plus 1 by N d. So, this is the expression for due to appearing due to the charge redistribution. Now once we know the charge distribution we can calculate the electric field electric field is calculated using Gauss law all of you know the Gauss law that Del dot E is equal to rho by Epsilon.

So, Epsilon is basically dielectric primitivity which is Epsilon naught times dielectric constant k. So, for one decays you can write Del dot is d by dx. So, you can say that dE is equal to rho by Epsilon dx. So, rho is if you see on the left side is q times N a. So, minus q times N a and again you can integrate from let us say minus x P to some x minus x P to some x. So, this is basically E at minus x P E at minus x is equal to q N a times Epsilon.

So, this is basically dx value is just x. So, this is x minus minus x p. So, this become x + x p. So, E at x p is 0 because to the left of this there is no is neutral. So, it will not give an electric field. So, electric field at axis basically q N a by Epsilon times x + x p so, this is basically increasing but this x is basically no oh it is minus q and here minus q N a. So, this minus simply means the direction of the field is in Negative x direction.

So, this field will be maximum at x equal to zero because at x equal to minus x p this is 0 and as x increases up to x equal to zero this charge is increasing after x equal to zero again positive charge will come. So, the charge will decrease and the field will also decrease. So, maximum electric field is at the metallurgical Junction and that is q N a x p by Epsilon and of course the sign will be negative because its N minus x direction.

So, now from the equation one you can substitute the value for N a x p here. So, you can get Epsilon times E Max now Epsilon is basically Epsilon naught times dielectric constant K or times E Max and that is minus q times N a x p. So, this is the expression here and N a x p is equal to N d x n. So, you can write like this also and if you substitute here you can write in terms of depletion width. Now if you move from left to right plus have a view of band diagram also here this is Fermi level and left side is P type.

So, the band is somewhere here valance band. So, this is U times V bi. Now if you see here these are the energies energy is minus q times the potential because minus q is the charge on electron. So, these are the electron energies. So, the corresponding potential will be V and this energy is obtained by multiplying the charge on electron with V. So, minus q times V that means the potential will actually be since energy is higher on left side. So, the potential will be lower here energy is lower the side.

So, potential will be higher this side. So, this will be the expression for V bi. So, potential will actually increase and you can see here also you move from negative charge to positive charge. So, this is a negative charge this is the positive of charge. So, field is in this direction. So, you when you move opposite to the field the potential increases and potential is basically you can recall E is equal to minus dv by dx.

So, V is basically integral negative integral E dx. So, that is basically effectively translate to the area of this curve. So, the area of this curve is a triangle basically because the field the K the charts concentration is constant therefore the field is linearly varying and field is linearly varying. So, it is like a triangle and whose area is going to give you the potential. So, the built-in potential is the area under this curve.

So, which is basically half times the base which is the width of the depletion region times the maximum electric field. So, half E Max times W the width of the definition region will give you the built-in potential. And for E Max you can use this expression from the previous equation and that can tell us what is the width of the depletion region.

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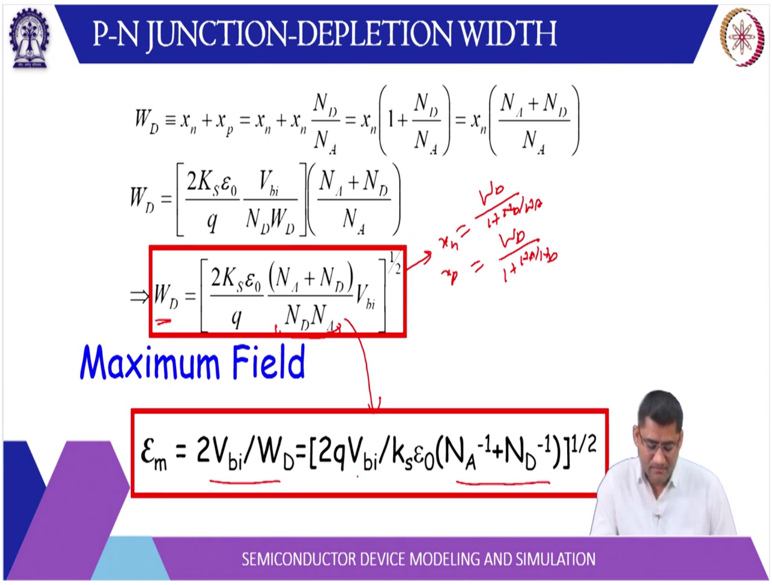

So, when you substitute these equations. So, you get this expression for the depletion region you can notice one thing here the depletion region is inversely proportional to this N a N d. So, if you have higher concentration on certain side then the depletion width will be smaller on that side you can get the expression for x n and x p also. So, x n is basically W depletion weight divided by 1 plus N d by N a.

So, if N d is more x n will be less similarly x p is w d by 1 plus N a by N d and if you substitute this previous equation V bi is equal to half E m times w d. So, here also you can express E Max in terms of 2 V b i by w d and you can substitute this expression for w d and you can find this E Max in terms of the doping parameters. So, E Max is basically is proportional to this built-in potential and the doping concentration.

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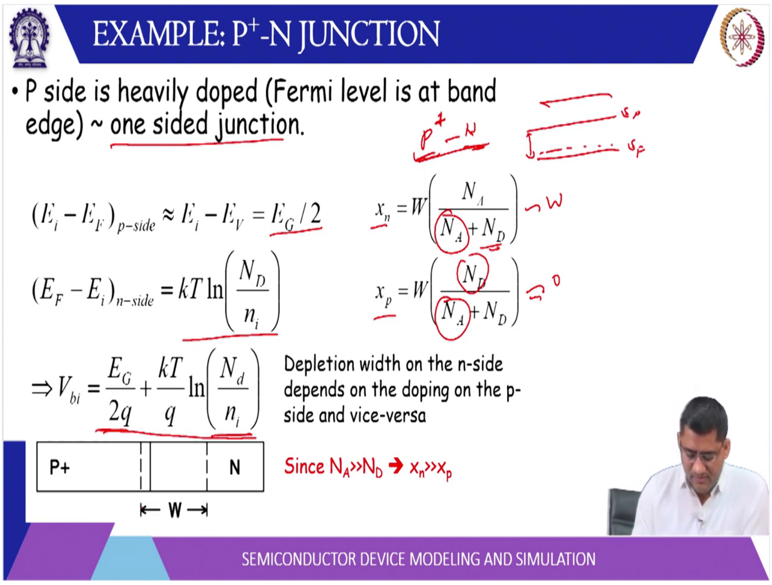

So, if doping concentration is higher you will expect a higher electric field and now we can consider one example of one sided Junction. Now one side is Junction is basically where one side is heavily dropped compared to other. So, you can take P plus N or P N plus. So, when you write plus here that means this region is highly doped. So, more than ten raised to power nineteen and so on.

So, what will happen in such scenario let us say peep side is highly doubt then Fermi level will be very close to the valance band or it may in fact be on the valance band edge itself. So, on P side E i minus E F will be almost equal to E G by 2. So, and of course on N side it is normally doped. So, it is kT log N d by N i and when you add the 2 you will get this expression. So, that means this built-in potential.

Now simply depends on the donor concentration on the N side because P side is more or less fixed to E G by 2 and of course if you look at the expression for x n and x p that we have derived and the depletion width on P sat will be very very small because the doping N a is quite large. So, if N a is quite large then N a by N a plus N d you can ignore N d and this will be close to w. So, this doping width almost appears on the N side and on the P side this end is much smaller than N a. So, this will be close to zero.

So, now you notice here the depletion is an entirely lies on the N side. So, this is called one sided P-N Junction.

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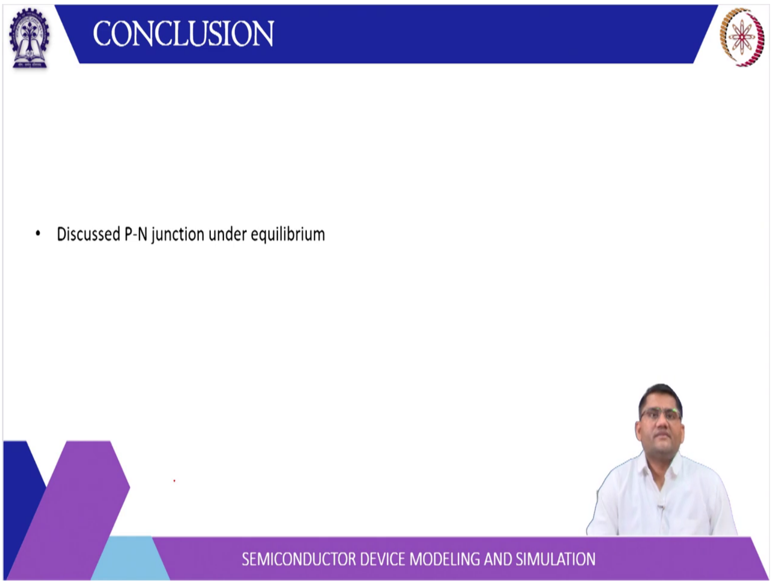

So, in this lecture we have discussed the P-N Junction under equilibrium in next class we will consider P-N Junction under bias thank you.

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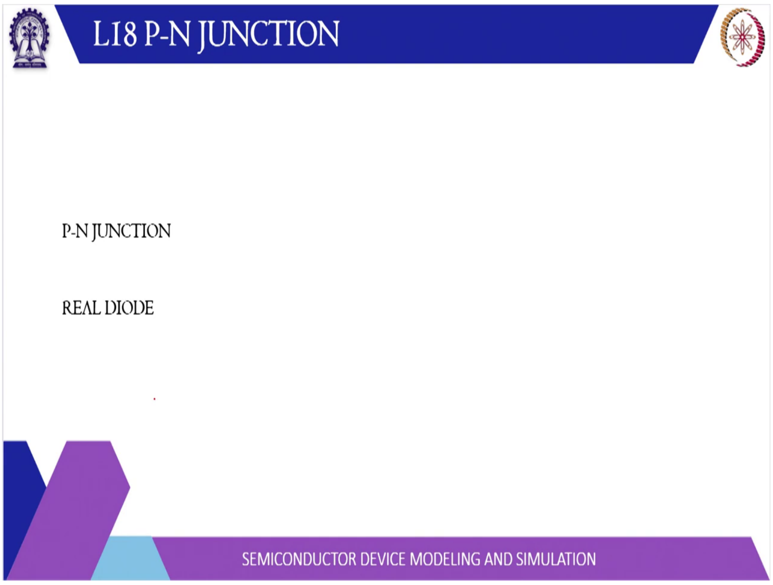

Hello welcome to the continuation lecture of on P-N Junction. So, we have discussed about the P-N Junction we have discussed the electro aesthetic of the P-N Junction then we drive the current equation using solution to Magnetic array diffusion equation.

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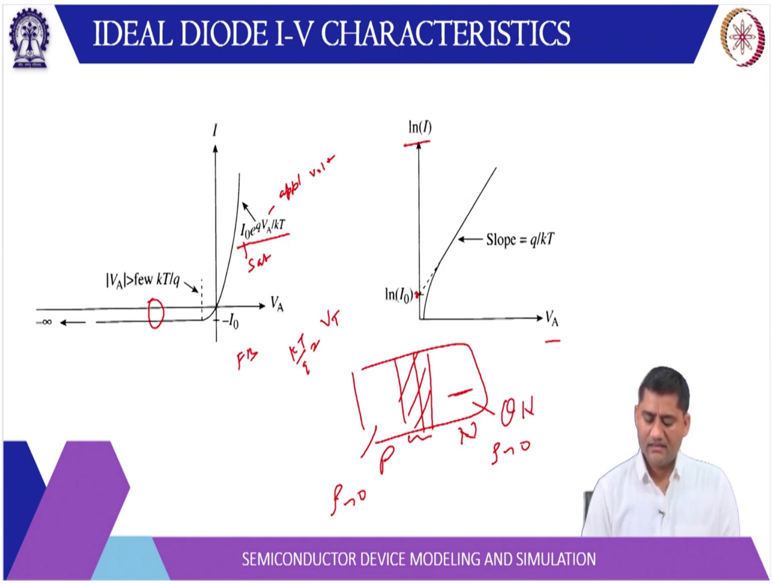

Then we develop this thing using charge conservation model. So, in summary we can write that for ideal diode current is given by some I naught times exponential q V by kT where I naught is the saturation current or reverse saturation current and V is the applied voltage and T is the temperature k is a bolt span constant and q is the charge on electron and kT by q is non **(()) (34:25)** called thermal voltage V T.

And if you notice here in forward bias when the voltage is greater than zero or P type is positive this current increases exponentially. In the reverse bias there is a constant current at that basically you can go to any voltage in the reverse bias the current remains constant. Please recall that we drive this expression under the assumption that in the depletion region. So, this is your let us say P-N Junction and this is a depletion region.

Here in the depletion region there is no recombination or generation that was one major assumption. Another assumption was we assumed this as quasi neutral region. So, that means in this region charge was roughly zero and this are also the charge is roughly zero. So, all the charges in the depletion region only. Now we will consider what happens if we consider the realistic situation.

We can consider the generation recombination in the depletion region and we can also consider there may be some finite electric field in this region also. So, in certain situation these effect becomes dominant then of course we have to include them. And this right side curve is basically is a plot of logarithmic current along y axis and the applied voltage and this is basically a linear more or less linear here and if you extend this linear region why it intersect the y axis at log of I naught.

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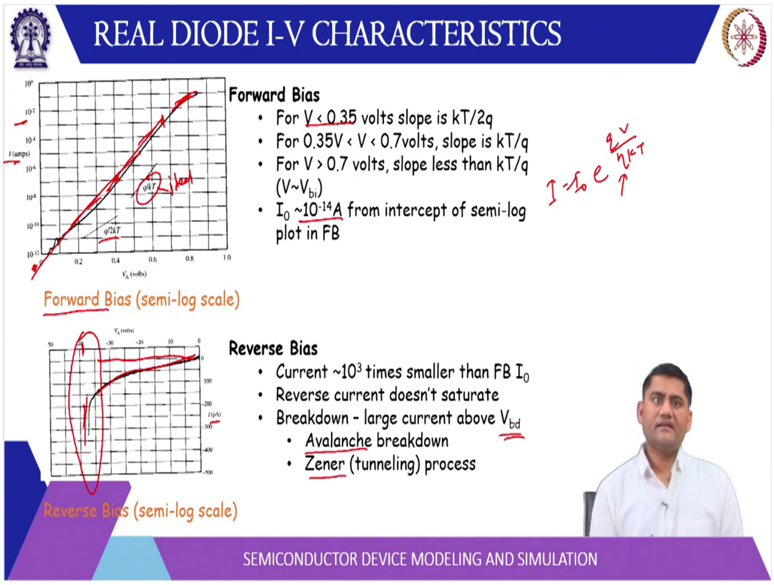

This is the; if you consult some data sheet for a typical diode you will get characteristic like this. So, this is forward bias. So, in forward bias in the region around 0.35 to 0.7 this slope is q by kT. So, that means here the diode is behaving like an ideal diode below this region the slope is less above this region also slope is reduced. So, this can be approximated by q by 2 kT. So, for voltage less than 0.35 and greater than 0.7 of course it can be again not kT by q but some other slope.

So, that is why for Zener diode equation we use I is equal to I naught exponential q V by eta kT where eta is a identity factor and it is a function of voltage and other condition. So, in different region you can use different data for different operating condition. And the reverse saturation current is typically order of 10 is to power minus 14 ampere that you can get from the intersection if you extend this linear region it will intersect somewhere here so, which is around tennis minus 14.

In the reverse bias you notice we expected it to be a constant current but it is gradually increasing and if you look carefully it scales as square root of the voltage and the current is fairly small if you see here is order of Pico ampere and this one is in if you see here around this region this order of few Milli ampere. But 2 things you can notice in the reverse bias it is not constant and at certain voltage there is a sudden change.

So, this slope becomes quite large this region we call a breakdown and there are 2 main mechanisms that are responsible for the breakdown one is called Avalanche breakdown other is called a Zener breakdown. So, and the voltage at which the sudden increase in the current appears that is called breakdown voltage. So, reverse saturation current is not saturating rather it increases and at certain point or that certain voltage there is a large reverse current due to the breakdown.

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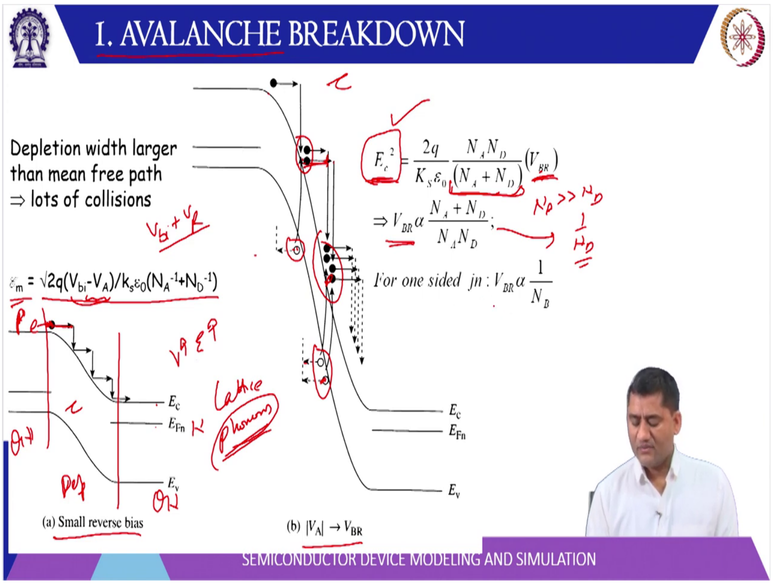

Now let us discuss one by one this figure is for small reverse bias. So, in small reverse bias what happens this is quasi neutral region this is also cosine neutral region and this is your depletion region. So, typically in the reverse bias this depletion width as you increase the reverse bias this depletion width will increase. So, it is long enough and in the depletion region carriers are also a small in number.

But as you increase the voltage what happens the electric field increases as you can see here electric field is given by square root of 2 q v b i minus V A. So, this is basically if reverse bias then it add up basically. So, you can say V bi plus V R because we applied is for forward bias. So, in Reverse bias this is negative. So, you can say V bi plus V R. So, it increases as a square root of voltage. Now let us say electron moves from N type or P type because in Reverse bias is a minority carrier that will go.

So, this is N type this is P type those formula is close to the conduction end here then electron a minority carrier will move from here and it will get accelerated and it will move certain distance after which it will get scattered. So, that time is roughly fixed the time between 2 collisions is called scattering time. So, in that time it get accelerated by this field. Now in the small reverse bias the field is a small.

So, it gets a energy but it is not high enough to knock out another carrier from the valence band so what it does it transfers the energy to the lattice vibration or phonons. So, these electrons move around and they transfer their excess energy to phonons so, that basically cause some kind of heat that is it. So, phonon is basically kind of heat or lattice vibration but at high electric field what happen the energy acquired by this electron is quite high.

So, you can see the right figure here when the reverse bias voltage is close to the breakdown voltage. So, this for the small distance there is a large change in the potential. So, their energy changes by quite a bit amount and that is comparable to the bandgap. So, what will happen as it collides whenever another electron here the energy released can be taken by third electron and it can produce a electron and whole pair and that effect actually multiplies.

So, what about this electron goes to right it produce electron hole pair then electron hole pair jet is generated then. Now 2 electron go and hole will move to the left. Then four electrons will go to the right and 2 hold to the left. So, these all that are coming here these all that are coming here they will again generate another electron hole pair so that way when this multiplication is beyond certain critical value we have this avalanche breakdown.

So, the current actually increases very rapidly. So, now what will limit the current the current will be limited by the circuits? So, circuit will have certain resistance. So, like in Zener diode you see where the effect is generous not the Avalanche breakdown but these are used in photo detectors where very small number of photons are there. So, if you have to detect it then this APD called Avalanche photodiodes are used there.

So, this breakdown voltage give rise to this maximum electric field and we can say this maximum electric field we are critical electric field at which the energy acquired by the electron for a distance travelled of Tau the mean collision time is enough or comparable to the bandgap. So, that it can knock out another electron that that is the critical electric field basically and if you compare it this is dependent on this applied voltage and the doping level.

So, for if you know the breakdown voltage then for a given breakdown voltage you can find out what is the corresponding doping. So, if you change that open then the breakdown voltage will change because this critical electric field is fixed basically. So, you can say that because critical electric field is fixed. So, this product has to be constant. So, that means your breakdown voltage proportional to N a plus N a N a plus N d by N a N d.

And if it is let us say one sided junction let us say N a is much larger than N d. So, then this expression will simplified to 1 by N d. So, the lower doped side basically. So, if N d is more than much larger than any then this will be 1 by N a. So, this is basically for one side rejection breakdown voltage is one over the doping concentration of lower doped side and you can understand this way also the lowered outside the depletion region will extend maximum on the lower doped side. So, there all this multiplication will take place.

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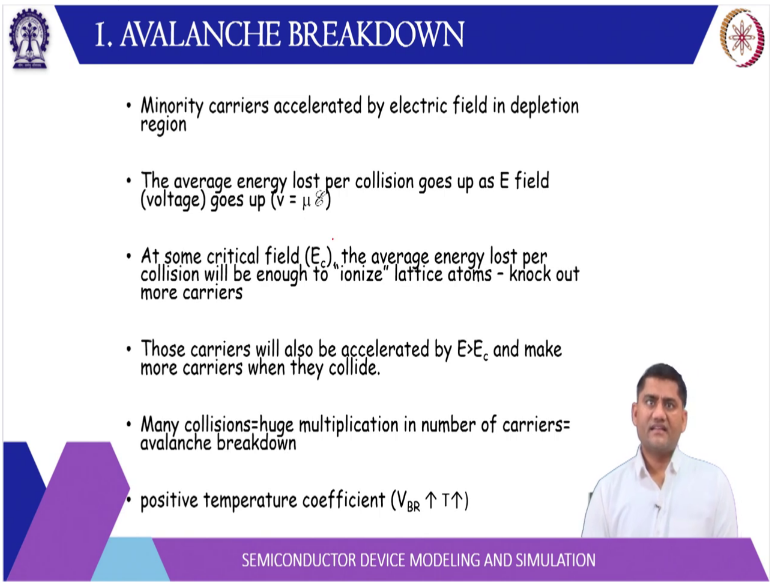

Now these magnetic areas are accelerated or the electric field. So, this we have already discussed and at high field of course this V equal to Mu it does not apply but in the linear region up to certain point this is true that V is equal to Mu a and then of course when there is a critical electric field the average energy lost is in enough to ionize the lattice atoms or knock out the electron.

So, when the applied voltage is such that the electric field in the depletion region goes to beyond critical electric field then the surveillance breakdown take place. Another thing is important here this avalanche breakdown is positive temperature coefficient. Now why does it apply positive temperature coefficient not 11 let us say you increase the temperature then if you increase the temperature then the random thermal motion or the thermal velocity will increase if thermal velocity is more then the time between 2 collisions will be less.

So, now for a given electric field if the tau is reduced then the energy accord will be less because. Now it is accelerated with that electric field for a smaller time. So, let us say for let us say T 1 the critical reactive field was E 1 E c 1 if T 2 is more than t one then and let us say this is Tau one. So, now Tau 2 will be less than Tau one for a greater temperature but it is the combination of these 2 that decides that electron will get sufficient energy to ionize.

So, if temperature this tau is reduced then your E c 2 has to be more than E c 1. So, that they get sufficient energy within a smaller time. So, that means your breakdown voltage will increase. So, as the temperature increases the breakdown voltage increases and that is a characteristic of avalanche breakdown.

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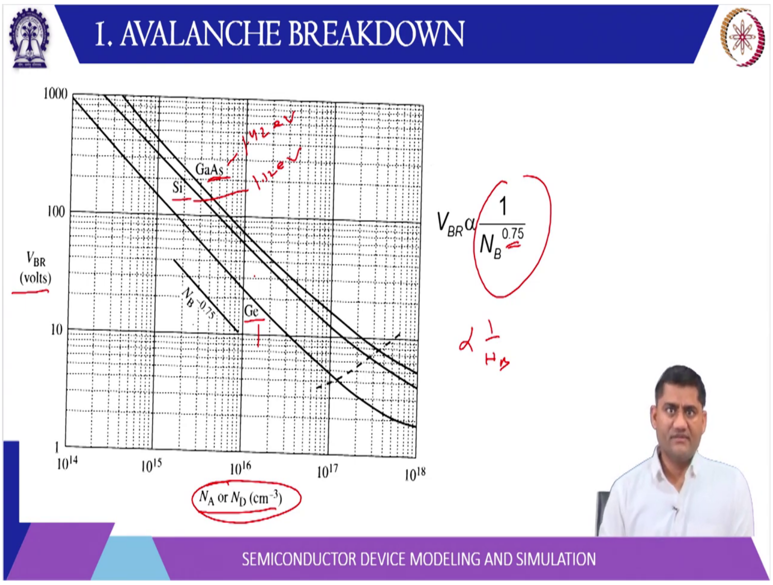

And this is the curve which relates the breakdown voltage versus the doping in case of these materials gallium arsenide, silicon and germanium and as we drive that it is roughly proportional to one over NV. And if you fit it with the experimental value you get around power 0.75 and with the increasing doping the breakdown voltage is actually reducing. Now this doping is on the lighter doped side.

So, this is our one sided junction. So, and you can also see the breakdown voltage for gallium arsenal is more than silicon that can be explained as the band gap for the animation is 1.42 electron volt for silicon is around 1.12 electron volt germanium is even smaller so, around

0.67 electron volt. So, because the bandgap is less so, the breakdown voltage is also less because. Now energy record is smaller compared to gallium arsenide in Silicon and compared to Silicon less energy required in germanium.

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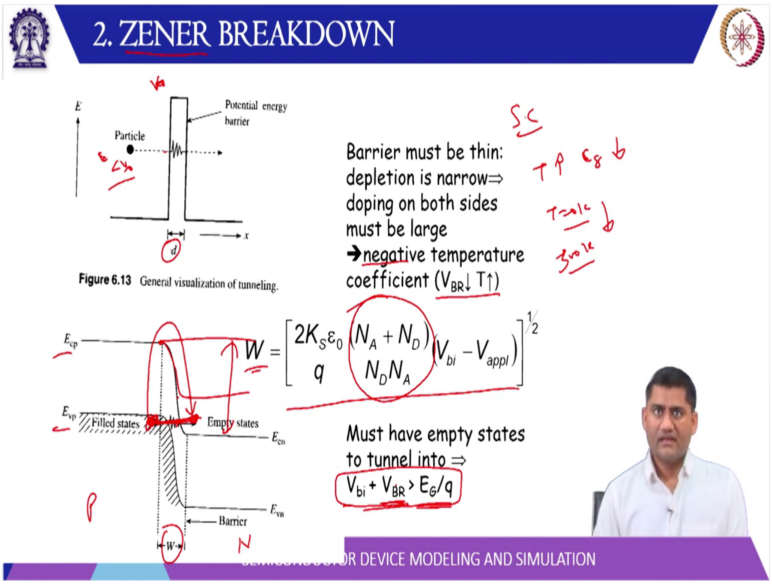

Now the second mechanism is the Zener breakdown in case of Zener breakdown the mechanism is the tunnelling. So, if you look at this picture here let us say this is some potential barrier with height V naught and the barrier thickness is d. So, this particle if thickness is small comparable to the de Broglie wavelength of this particle there is a finite probability that this electron can go over this barrier even though its energy E is less than V naught the the energy of the barrier.

So, in case of P-N Junction diode let us say this is your band diagram. So, this is the balance band conductor vent on let us say P side and this is the conduction balance band on the N side and this is a depletion width. Now there are electrons here because in P side this is this has some electrons here some failed States some empty state. So, some field electrons are here in case of this side there will be some electron some empty state.

So, these electrons from the balance band they have the same energy as the electrons on this side. So, this electron can easily go here the only thing is that it has to cross over this barrier but if this thickness is sufficiently small then there is a finite probability for this electron wave to exist on other side also. So, if the depletion width is small that expression we have valid drive if the depletion width is small then there is a possibility that this electron can tunnel through this barrier.

And the mechanism responsible for this breakdown is the tunnelling and we call this as zener breakdown so, large number of electrons are here because this is field vent and they can cross over. So, the relation is basically given like this that the V bi plus V br. So, V bi is the built-in potential V is the replied reverse bias. So, these 2 voltages are larger than the bandgap energy. So, this basically this is this is the V bi plus V br this is larger than the bandgap energy.

Because if it is smaller than bandgap energy then it will not go up to here it will remain somewhere here. Now this electron can tunnel through because tunnelling requirement is that initial energy and final energy there should be same and of course this width will be small if this doping is large because it is universally proportional to the doping. So, for high doping on both side we can accept expect a zener breakdown mechanism.

And another thing you can notice here compared to avalanche breakdown here the the temperature coefficient is negative that is as the temperature increases the breakdown voltage decreases that is contrary to the avalanche breakdown. Now what happens here in case of semiconductor as the temperature increases the bandgap actually decreases we can require you can recall the discussion regarding the band structure where we showed that at low temperature zero Kelvin there was some bandgap.

At 300 Kelvin the bandgap was reduced and as you increase the temperature the bandgap reduces. So, as if you increase the temperature bandgap has reduced. Now if you look at this relationship if bandgap is reduced the V br requirement is also relaxed. So, you will require a smaller voltage for a breakdown. So, as temperature increases the breakdown voltage decreases. So, this is also used to find out whether the breakdown mechanism is avalanche breakdown or zener breakdown you can find from the temperature coefficient.

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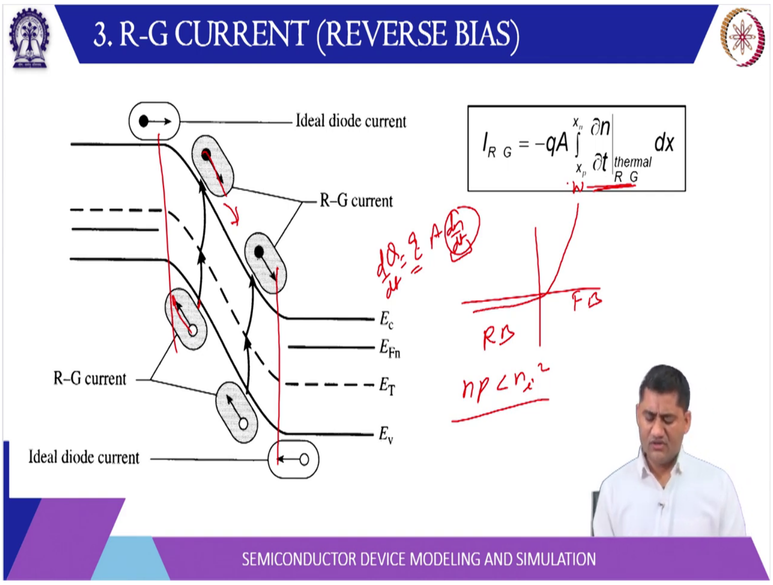

Now let us look at the IV curve of a P-N junction diode. So, you can recall here the IV curve basically look like this for ideal diode. So, in forward bias exponential in Reverse bias it is a constant and that was the case when we ignore the generation recombination in the generation recombination in the depletion region. Now in real diode there is a certain amount of generation recombination in the depletion region.

So, you can see this is a depletion region. So, depletion means number of carries less. So, that means the mechanism that will be there will be generation because here n p product will be less than n i Square so, there will net generation in this region. So, when the electron role pair is generated then that will flow according to the field. So, if electrons are generated then electron will flow down L if all is generated it will go up like this.

So, some current will flow due to the generation recombination and we can estimate that current by simple expression number of carriers times q times the area of cross section times the number of carriers. So, number of carries is proportional to the generation rate of these electrons. So, this is total q and dq by dt will be d by dt of this. So, q and a are constant. So, you can write dn by dt. So, this dn by dt is a thermal generation rate.

So, and of course electron is a charge minus q. So, you can write minus q times dn by dt and you integrate over the width of the depletion region this is 2 integrate of the width of the depletion region. And if we assume that the rate is constant that we can find out for indirect bandgap semiconductors we have this SRH recombination sock layer read all mechanism.

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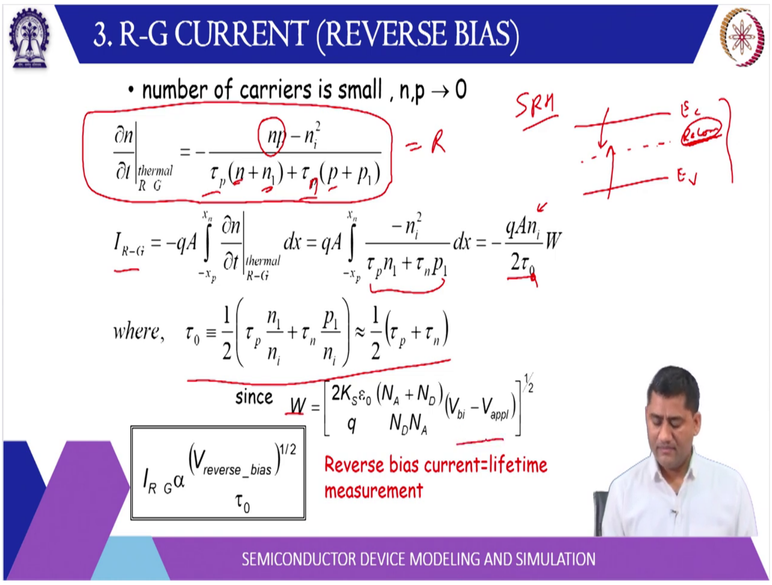

So, where the net recombination rate this is a net recombination rate is n p minus n i Square divided by Tau p times n plus n 1 plus Tau this should be Tau n i think Tau n times p plus p 1 where n p is the carrier concentration electron concentration whole concentration ni is the intrinsic carrier concentration that is fixed at a given temperature and the Tau p are basically carry a lifetime for Tau p and Tau and carry light term for electron and all and n 1 p 1 are some constant basically computed constants.

So, in the depletion region n p product is small. So, you can ignore it compared to n i square. So, you can just write numerator will become n i Square divided by Tau V times and n is p g small. So, you can write this n 1 p 1 there in the denominator and this can be represented by some constant Tau naught let us say. So, you can write that this generation current is minus q a n i by 2 Tau times W is a depletion width and n i is the and tau is rated to the carrier lifetime.

So, and these are different situations where these approximation can be applied. So, it is kind of average if this of course we will discuss later on when we discuss the semiconductor describing equations we will drive this expression right. Now you can understand like this let us say this is your semiconductor this is the valance band this is the conduction band. So, apart from doping level there are certain deep impurity levels and they are somewhere close to the middle of the bandgap and these impurity level act as a recombination centers.

So, they will capture electron they will capture a hole and they can combine here because. Now these electrons will have to cross the half of the bandgap energy barrier. So, there they can easily recombine if there were no this recombination center then the energy required will be equal to the bandgap. So, this recombination set centers actually ease out the process of recombination.

So, they increase the recombination rate and the recombination rate actually depends on where these recombination centers are located. So, this n 1 factor depends on the position of this recombination center. So, with this by the detail model we can calculate these constants also. So, right now let us use this expression this is the expression for net recombination rate and we know that width is proportional to the square root of applied voltage.

So, you can see this generation recombination current in case of reverse bias the generation current is proportional to W by Tau and W is proportional to the square root of y s voltage. So, you see this is proportional to the square root of reverse bias voltage divided by Tau naught. So, that is why in the reverse bias we saw that current was increasing like this. So, up to this region before breakdown it is the generation current that is responsible for this kind of characteristic in the P-N Junction diode.

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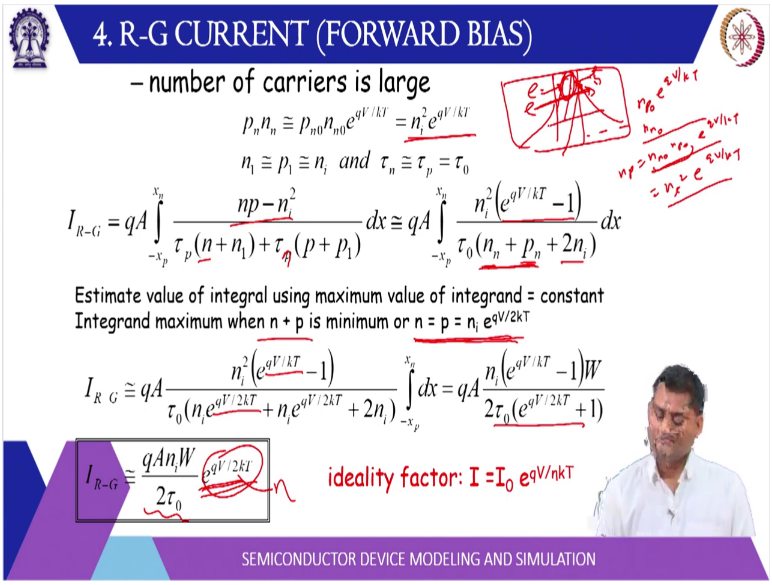

Then in case of forward bias there is a large number of carriers that are injected from both sides. So, now n p product is more than n i square. So, there will be net recombination if you look at this expression n p product is more than n i Square. So, there will be net recombination. So, we know that n p product is if you recall this P N Junction this is a magnetic array diffusion equation.

So, here it was let us say this is n p naught exponential q b by kT that was maximum n right and n naught remains m. So, if you multiply these 2 what you get you get n n naught n p naught so, np product s exponential q v by K T. So, this is a product. So, this is n i Square n p naught n naught. So, this is N i Square Times exponential q v by kT. So, this is what written here that P-N product is N is for exponential q b by kT and that we can substitute in this expression for the recombination current.

So, the numerator becomes n i Square exponential q V k q V by kT minus one a denominator again as n and Tau P and Tau n ah. So, this can be replaced by Tau n times n n plus P-N plus 2 n i and because n and P-N is quite large you can ignore 2 n i here. So, this can be done n i exponential q b by 2 kT because this is n and P-N is the electron concentration inside electron concentration on P side.

So, so if n p product is this and then you can write n p if they are equal. So, that is basically some kind of high level injection is taking place ah. So, for high level or when this is maximum you can write n p is equal to they are equal and this is n i exponential q V by 2 getting. So, basically square root of this thing then if you substitute in a denominator. So, numerator has exponential q b by kT and denominator is exponential q V by 2 kT.

So, if you take the ratio of these 2 you will get exponential q V by 2 kT and then some pre factors q a and I W by 2 Tau naught the W is of course proportional to V bi minus V applied. So, that change in the applied voltage in the forward bias is very small. So, that will not play much at all. So, this will be the basically the controlling term exponential q V by kT. So, here 2 is identity Factor and that is applicable for smaller bias 0.35 to 0.7 and at higher bias also other factor will also come into the picture.

So, when large number of carries are flowing into other side and there is a net recombination in this region. So, you can visualize picture like this electrons come from here whole come from here. So, this electron hole dot go but they recombine here and they disappear. So, number of electron moving is much larger than so total current is electron crossing over plus electron recombining or hole crossing over plus whole recombining that is a total current.

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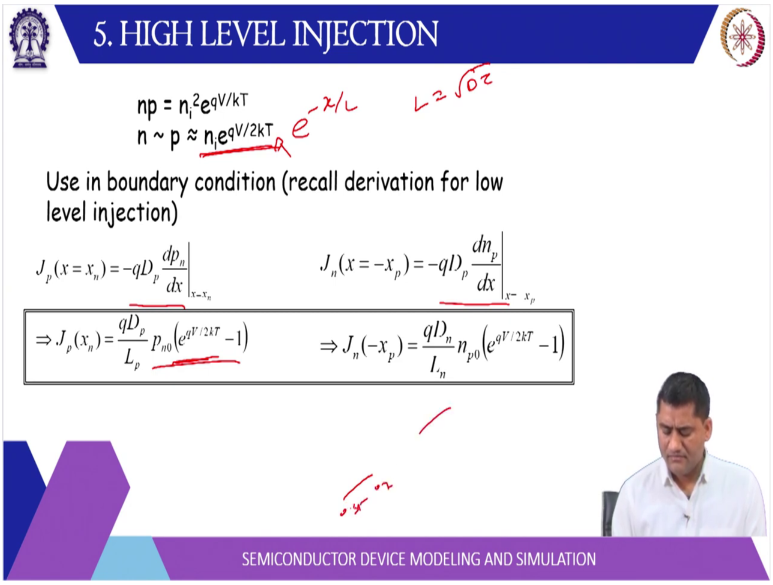

So, this is the case that happens between the point three five to point seven volt then at high level injection of course you can directly write this same thing n p product is n i Square exponential q V by kT and you can substitute this equation for the minute carrier diffusion in the quasi neutral regions and then of course when you calculate the diffusion current q dp times dp by dx for N site because holes are minority there and for electrons on P side you can write q dp times dn by dx.

And this is the expression for N and P and they are dependent or x is something like E to the power minus x by L where L is root of d Tau. So, so this will be basically q dp by L times P naught exponential q V by 2 kT. So, at high level injection also you follow this kind of characteristic exponential q b by 2 kT. So, this is valid for 0.35 to 0.7 and then sorry 0 to 0.35 and beyond 0.7.

So, both cases you have this kind of characteristic one is due to high level injection another is due to recombination.

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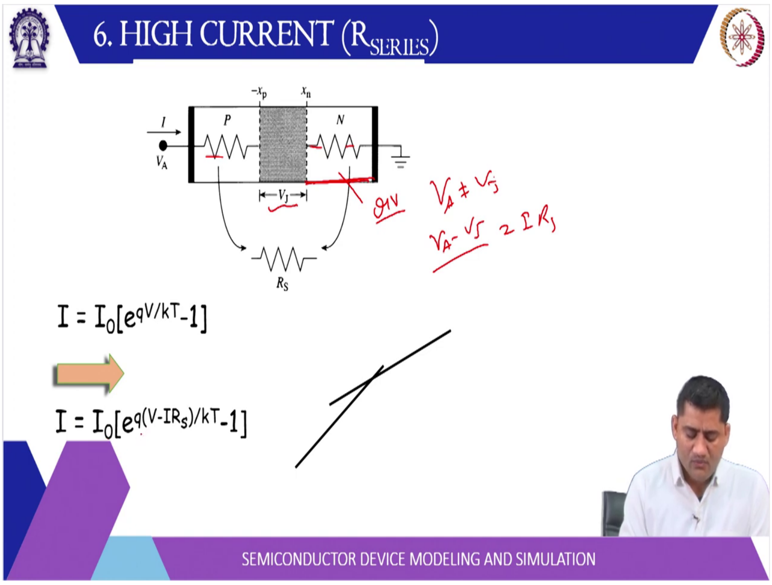

Now at even higher current this quasi neutral region approximation does not is not valid here. So, there will is there will be a finite drop in this region because there is large amount of current is flowing. So, although the resistance is small here but due to large amount of current there is some finite voltage drop. So, as we assumed that all the voltage drop appears across the junction that is not true. So, now V a is not equal to V j. So, V a is applied voltage V j is a junction voltage or across the depletion region.

There is some finite drop in this region also and that drop will be V a minus V j. So, or you can say it is also I times R s the reason the resistance of these 2 regions causing neutral regions. So, now your expression is I is equal to I naught exponential q V across the junction. So, that is V minus i R s by kT minus 1.

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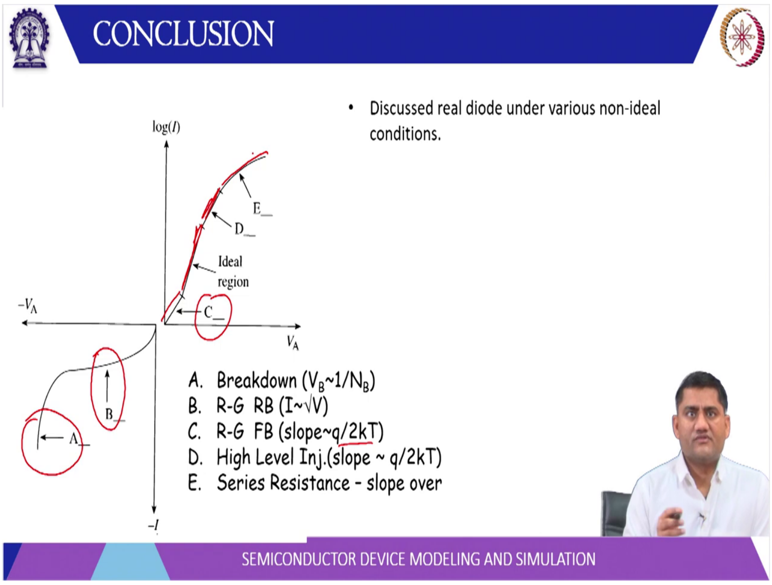

So, in summary we can say the IV curve of PN Junction consists of several regions where a is the breakdown region. The mechanism can be Avalanche breakdown which has positive temperature coefficient it can be Zener breakdown which has negative temperature coefficient then there is a recombination region the current due to the sorry generation this is due to generation.

So, current due to the generation of the carriers in the depletion region because they are less number of carries in the depletion region. At forward wise there is a injection. So, this region is basically due to the recombination and the slope is q by 2 kT. Then of course this is the ideal region then beyond ideal reason again due to high level injection and then due to the series resistance there is some slope change. So, we have discussed the real diode under various non ideal conditions, thank you very much.