Semiconductor Device Modelling and Simulation
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Lecture - 17
P-N Junction (Contd.,)

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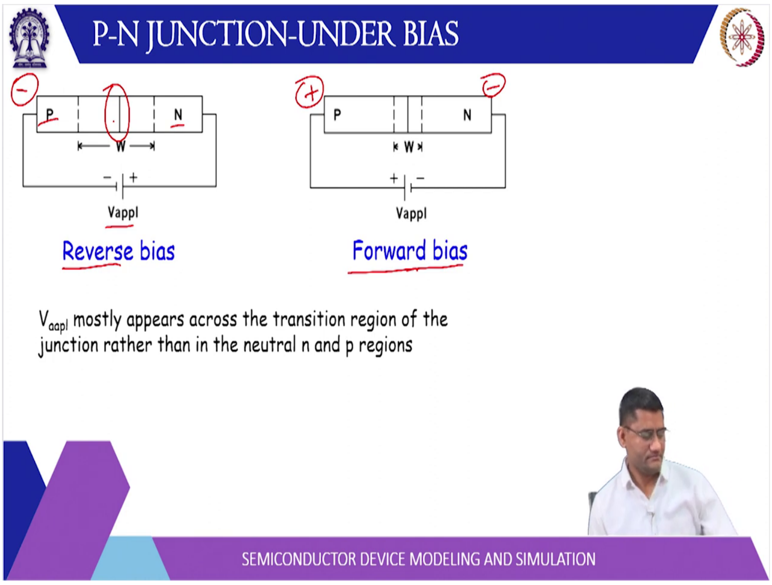

Hello, welcome to lecture 17 on PN Junction. We will continue our discussion ah. Now we will consider PN Junction under bias and we will derive the ideal diode equation. So, let us consider a PN Junction. So, this is P type diode this is N type diode. Now there are 2 types of biases one is forward bias other is reverse bias. So, in forward wise current actually flows and here P side is positively positive voltage applied on P side and a negative voltage are applied on N side or you can say it is a relative thing basically.

So, that P sub is positive related to n site and that bias is called forward bias and in this bias current actually flows. In case of reverse bias n side is negative with respect to P side is negative with respect to n side. So, in this case current does not flow in case of reverse bias this applied voltage mostly Falls across this depletion region that means the built-in potential which was across the depletion region that potential across the depletion region actually increases in case of reverse bias. In case of forward bias that potential decreases or you can say the barrier actually reduces.

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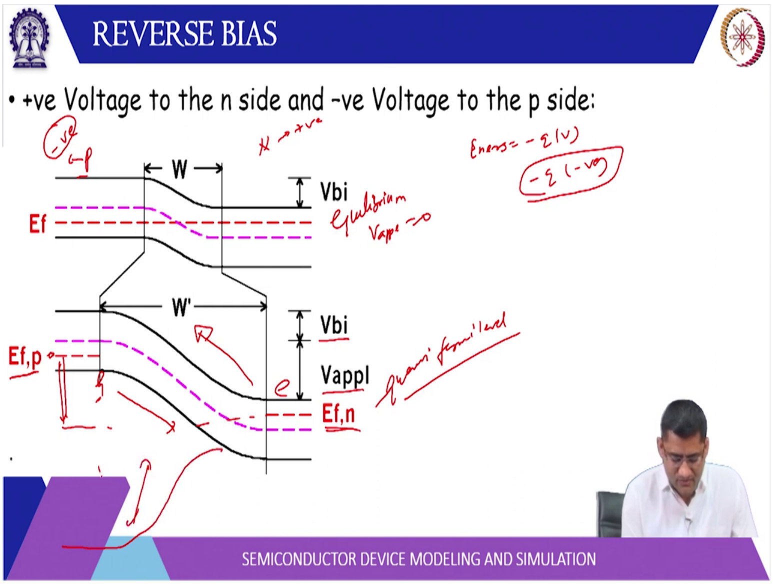

So, this is the typical band diagram this is under equilibrium when there is no applied. So, V applied is zero here. Now if we apply a reverse bias. So, reverse bias means this is P side this is N side. So, in Reverse bias P side is negative N side is positive that means a negative potential here means the Fermi energy will be more because energy is minus q times V. So, V is negative. So, minus q times a negative voltage will be a positive.

So, this Fermi energy is more on P side compared to N side. So, you see here. So, this is basically your applied voltage the difference between these 2 Fermi levels E F on P side and E F on N side. Another thing you can notice here. Now there is no single Fermi level we have to find 2 Fermi levels permeable on N site and Fermi level on P side we also call them quasi Fermi level. And of course when we refer to carry concentration on either side we use but that particular Fermi level.

So, if you see the barrier here. Now where here is this built-in potential + the applied voltage. So, the electron on this n site they see a bigger barrier now. So, the movement of these electron will be further restricted similarly whole on the P side they again see a bigger barrier here this up wheel is a barrier for electron because it requires more energy similarly this down L is a barrier for holes because this is + q times V or you can see from this you can also draw the potential.

So, potential will look like something like this. So, this is. Now V bi + V applied. So, this is a barrier for these holes basically.

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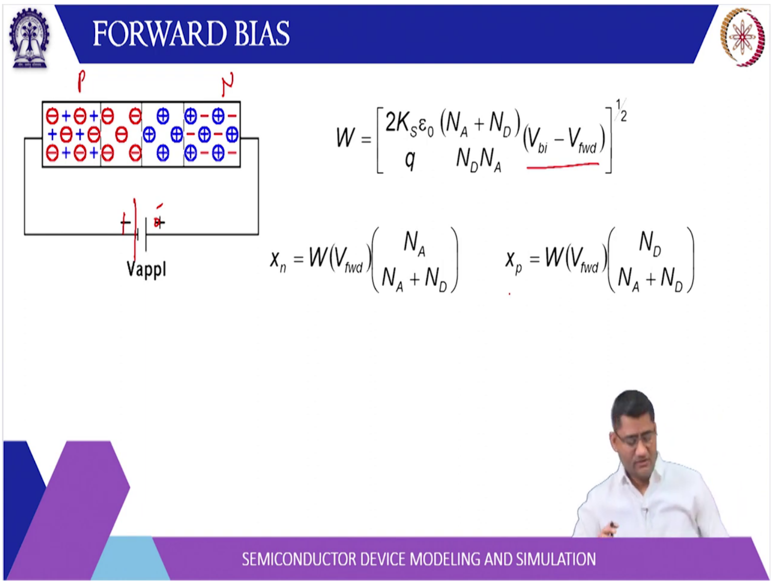

So, we can use the previous expression for the depletion width. Now the voltage across a depletion width is V bi + V applied or V reverse bias right. So, in the expression for the depletion width we will just replace this voltage by V bi + V applied right or V reverse bias. And similarly this x n will be total W Times N a by N a + n dx P total W Times N d by N a + N d. So, this potential applied under reverse bias increases the depletion width and that increase in the same ratio for the 2 depletion region.

Let us say you have one sided Junction. So, let us say you have P + N Junction right. So, the depletion width is small on P side larger on N side. So, due to this applied reverse bias both will increase but this P + side will increase less N side depletion width will increase more. So, it basically disturbs the equilibrium. So, E F is no longer constant and it basically adds to the effect of built-in voltage in case of forward bias P side is this P side this is N side.

So, P side would be positive. So, it is only positive here it should be negative here. So, this will basically reduce the depletion width and the expression for double depletion width we will have this voltage replaced by V bi minus V forward by S and accordingly this x n and x p will be. So, both side on the N side as well as on the P side the depletion width will be reduced and of course these electron and holes will see a smaller barrier.

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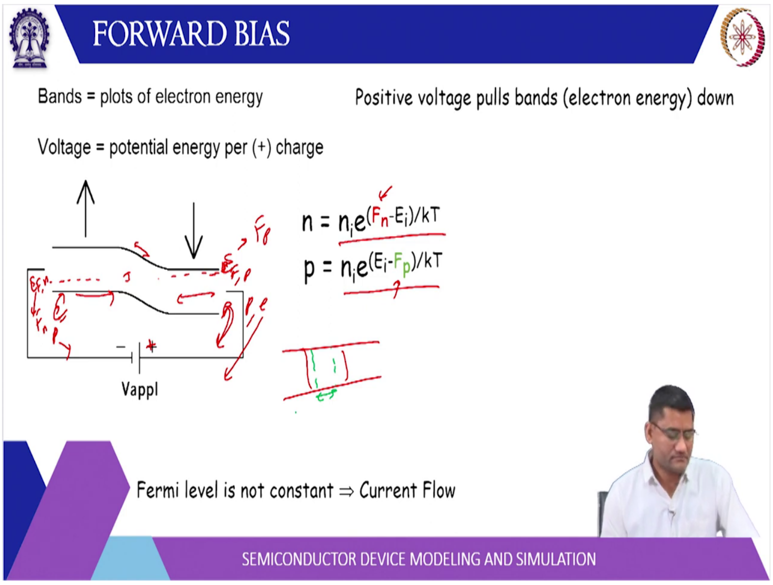

Now so, due to this applied bias this is positive. So, this is a Fermi level here this is a permeable here. So, there is a difference between these 2 is applied bais.. So, this is E F on P side this is E F on N side so this is also called F P this also called F N available on N side and the expression for electron and role is given by n i times exponential f n minus E I by kT and on P side n i exponential E i minus F P by kT where F P is the Fermi level on P side and F N is a Fermi lever on N side.

So, now Fermi level is not constant and therefore there is a current flow and you can notice here this barrier is reduced is smaller by applied voltage. So, what is happening basically this positive voltage is pulling the holes from here pushing the holes and attracting the electrons. So, these electrons will be attracted and also will be pushed. Similarly this negative on voltage on this side it will push these electrons and it will attract the holes.

Now these electrons are majority here. So, they will move towards the junction. Similarly holes are measured here they will move towards the junction. So, the depletion width which was something like this now will reduce. So, maybe you can use different colours. So, the electron will move here hole will move here. So, now depletion width will be smaller basically due to this applied forward bias.

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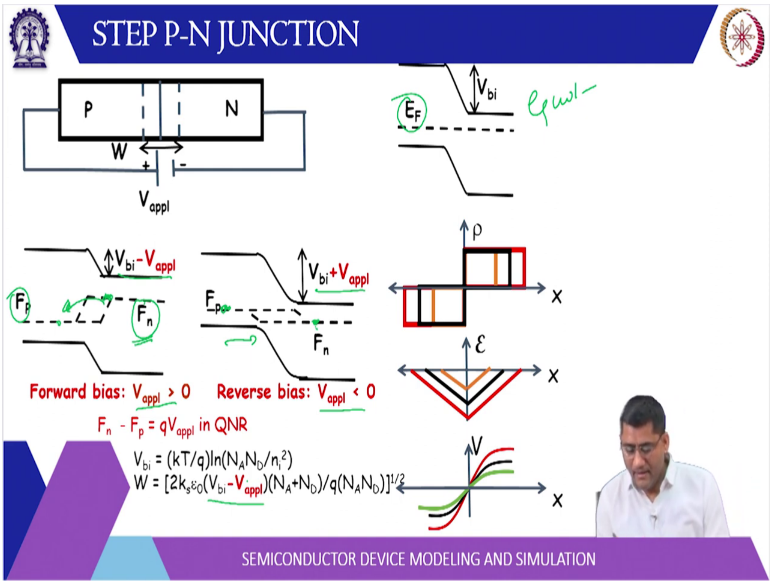

So, this depletion which is now basically functions of the applied voltage. So, in equilibrium this difference is V bi in case I applied forward bias this barrier reduces and these Fermi levels separate out. So, in equilibrium there are single Fermi level in case of forward bais we have 2 Fermi level F N and F P and F N is above F P. So, that means another thing you can notice here because Fermi level is tells you the probability of finding electron.

So, this Fermi level for the N is on higher side. So, here probability of finding electron is up here probability of finding electron is up. So, this is above it has more energy. So, it will tend to send the electron here because here it has more probability of finding electron. So, the diffusion current will actually increase because this is N-type region it has more number of electron and it has higher probability to give the electron because this Fermi level is above.

In case of reverse bias this barrier is increased to V bi + V applied or V reverse bias. Now this permeable is below. So, the probability of finding electron is up but it is lower than the F P. So, now it cannot give electron. So, that means the diffusion of these electrons from N side similarly the division of holes from P side because the probability of finding hole is half here and here it is more.

So, now this side cannot give the holes also because here probability of finding all is more than this point. So, this slide basically summarizes the three cases the equilibrium the forward bias and the reverse bias and we can use the general expression for the depletion width V bi minus V applied where V applied will have a positive sign for forward basis and it will have negative sign for reverse bias.

So, this is the expression for reactive field as you increase the applied bias it appears like this and this potential also increases. So, as you increase applied wise and reverse basically. So, this is forward bias this is equilibrium this is reverse bias and similarly this is forward bias equilibrium is the reverse bias.

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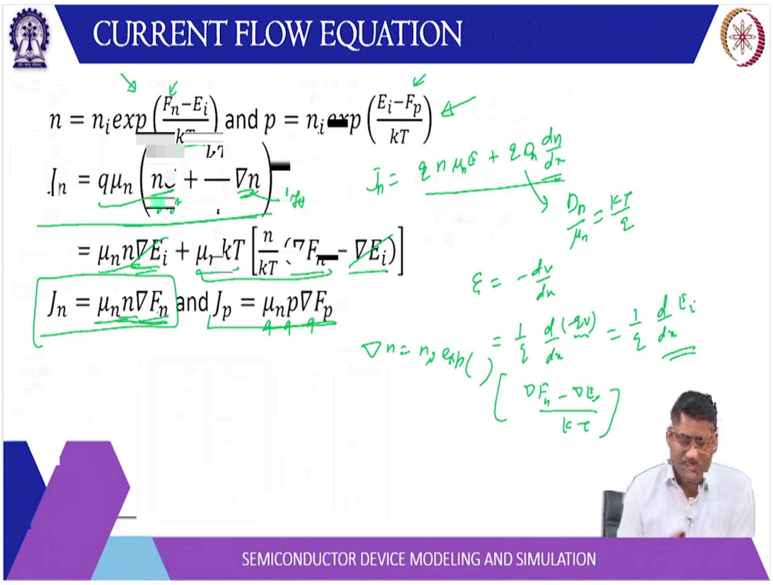

Now this equation we already know there are 2 components here one is the drift another is the diffusion. If you recall that J is q times n times mu times E is the drift Plus q times D times D n by dx the subscript n here. So, we skip 10 here this is the current density for electrons this is for 1D basically. In 3D this D n by dx get replaced by gradient of n. Now there is a relationship between this d and mu so this is called Einstein relationship.

So, D n by mu n is kT by q. So, that can be easily derived. Now this is applicable for non degenerate semiconductors and for non designed some semiconductor we can write these Expressions also n equal to n i E F minus E i by kT and P is equal to n i E i minus E F by kT. Now because under bias condition we have 2 different Fermi levels quasi Fermi levels. So, it is replaced by F and here and F P here. Now when you add these 2 terms electric field electric field is basically minus T V by dx.

So, if you multiply and divide by q so, 1 over q times d by dx of minus q times V. So, minus q times V is the energy. So, your E c, E v and E i these all are electron Energies. So, you can write it as one over q times d by dx of electron energy E i the internal the intrinsic energy level or you can write E C or E V also that does not matter basically it will give the same result. So, if you look at the first term the drift current. So, this can be written as n times mu n times the derivative of E i.

So, this is Del E i solely on right side q mu times kT by q. So, mu kT times dn. So, if you take the derivative from for the N here you can write n i exponential derivative of this term. So, derivative exponential is exponential. So, Del n is basically you can write n i exponential term no change then this is basically Del F n minus Del E i by kT. So, that is done here. Now if you see here these 2 terms will cancel out this Delta a and Delta i because kT will cancel so, mu and even.

So, what you will have basically you will have only this middle term. So, that is Mu n times n times derivative of Fermi level. So, you can also write the expression of current just in terms of the Fermi level. So, gradient of Fermi level basically tells you the current flow. So, the current flow due to electrons is n times the mobility of electron times the gradient of Fermi level. Similarly current density due to holes is the whole concentration times their Mobility times the gradient of the Fermi level.

So, that you can see in the previous slide there is a gradient of Fermi level here there is a gradient of Fermi level here. So, there will be current. Now you notice here in case of reverse bias also there is a gradient of Fermi level but gradient is Fermi level is there but corresponding electrons and holes are not there they are depleted of these carriers. So, therefore in case of reverse bias although there is a gradient of Fermi level the current does not flow. And in case of forward bias carries are there as well as the gradient is there therefore current is flowing.

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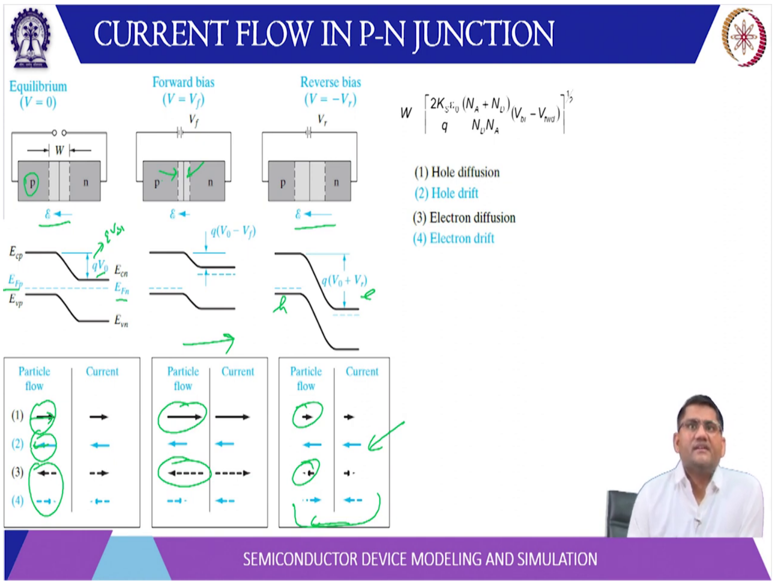

Now here you can see the summary. So, under equilibrium the built-in potential is the q times V bi written as V naught here and there is a single Fermi level. So, E FP and E FN they have a silicon cite and you can also notice the particle flow. On P side holes actually diffuse. So, this black line is the hole diffusion and you see the direction of electricity it is opposite. So, hole will drift in opposite direction.

So, this drift of the hole and the diffusion of the holes they are equal in magnitude. Similarly the drift of electron and the diffusion of electron they are equal in magnitude and they cancel out. Now when we apply a forward bias what happens? When you apply forward bias these holes are pushed here the electrons are posed here. So, this diffusion component actually increases for both the electron and holes.

The drift component does not change that much. So, it remains more or less same. In case of reverse bias this depletion width is more and therefore the barrier seen by electrons here holes here is larger. So, the diffusion actually reduces for both electronic holes. The drift remains more or less same may be slightly increase because now there is electric field. So, you see there is a gradient of the electric field but there are no carriers to be carried by that gradient current does not increase.

So, drift current more or less remain to the same value. So, in this case there is a net current flow in opposite direction which is small. In case of forward bias there is net current flow in forward direction which is large and due to the diffusion. In case of equilibrium individual current component cancel each other. So, the net current flow is actually zero.

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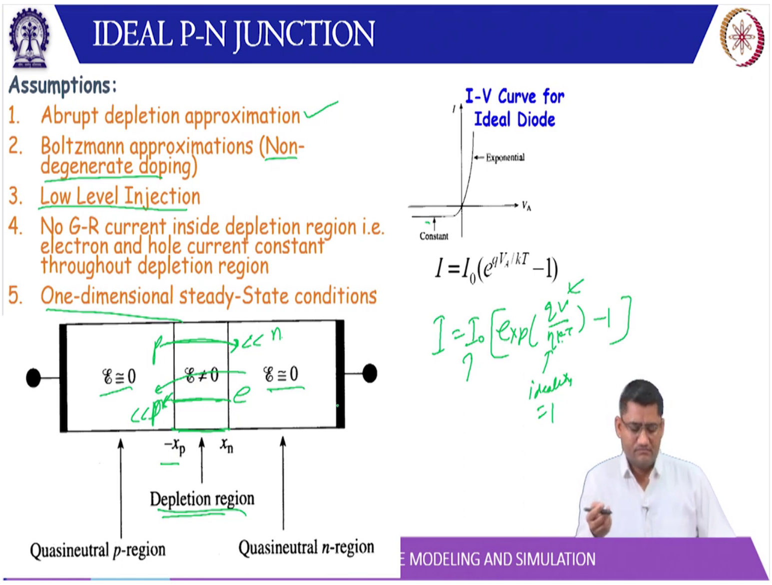

Now we will drive the IV current equation for ideal PN Junction diode. You can recall that the current equation for a diode is given by some I naught exponential q V by actually eta kT minus one. So, this I naught is called reverse saturation current and V is the applied voltage q is the charge k is a Boltzmann constant T is the temperature eta is called ideality Factor. So, for ideal diode this is equal to one times minus one. So, this minus 1 is basically there because at V equal to zero cut no current should flow.

So, exponential zero minus one so, that basically takes care that current is zero. So, this curve is exponential curve here with a almost constant current in under reverse bias a constant small current under reverse bias. So, for ideal PN Junction we have some approximation. So, of course first we assume there is a abrupt depletion approximation and the dopings are non degenerate. So, non degenerate doping means we can use this expression n is equal to n i exponential E F minus E I by kT and so on.

And the applied voltage is not very large so, that we restrict ourselves to the low level injection. Now low level injection is defined as where the let us say this is on whole side. So, holes injected from left to right these injected holes is much less than the majority carrier concentration here. Similar injected electrons from this side is much less than the majority electron concentration on this side hole concentration on this side.

So, the injected carrier consultation when it is smaller than the majority carry consultation we call it low level injection and of course if the injected carries are high we call it high level injection and another approximation we make that inside the depletion region there is no generation recombination. So, the electron move entering from the N side emerges on the on the P side without recombining in this region.

Similarly hole entering this depletion emerges out on N side without recombining. So, this is one assumption although not true but it simplifies our calculation and then of course later on we will consider these effects separately and here we are considering the one dimensional steady state case. So, we can divide this PN Junction into three regions one is depletion region and on either side of the of the depletion region we have quasi neutral regions.

So, this is quasi neutral N region quasi neutral P region. So, quasi neutral means there is no field there basically. So, all the applied wires falls across the depletion region. Now you will learn it why it is so, we will justify it also because the number of carries or is quite carriers is quite large here. So, for moderate amount of current to flow it does not require that much electric field.

So, the potential drop across this quasi neutral region is very small. So, we can consider it as if the electric field is almost zero.

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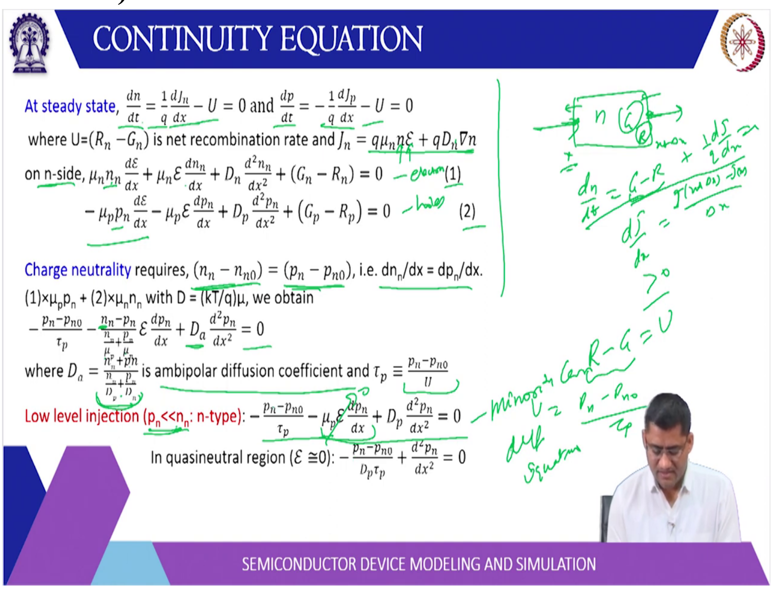

Now in deriving this equation we use one property called the continuity equation. The continuity equation is something like this you consider this box and inside the box let us say there are electrons and what is the rate of increase in the concentration of these electrons. So, rate of change let us say D n by dt. Now what are the different factors there can be a generation of carriers there can be recombination of carrier. So, this D n by dt is proportion to the generation minus recombination.

And another factor is the current flow. So, there will be some current entering this and there will be some current leaving this. So, let us say this is at x this is at x + Delta x. So, current is entering current is leaving. So, current is entering means electrons are moving away current is leaving means electrons are entering into the region. So, so the dj by dx is basically j at x + Delta x minus jx by Delta x. So, if j at x + Delta x is more.

Then more if this is positive let us say then more number of more amount of charge is flowing out and less amount of charge is flowing in so, this j actually is in terms of positive charge. So, in case of electron this if dj by dx is greater than zero that means more electrons are entering here and less electrons are exerting at the this interface. So, that means dj by dx is portable will increase the number of electrons here.

So, you can write + dj by dx here. Now dj by dx is basically related to the charge. So, you have to divide it by q. So, 1 by q times dj by dx is the net rate of increase in the electrons in this region. So, you can write this D n by dt like this. And of course in equilibrium this has to be zero and this G and R. So, there is an R is a recombination G is the generation. So, R minus G is a net recombination and V represented by U.

So, you can write D n by dt is one by q times dj by dx minus U and in HTT state it is equal to zero. Similarly we can write the content equation for holes. So, D p by dt is minus one by q dj by dx minus U which is again equal to zero we know that the current is given by these 2 terms drift + diffusion and when you substitute it here. So, you have there are 2 terms which can be dependent on x.

One is a carry concentration that is electric field. So, you can substitute here on N side. So, on N side you can write both the candidate equation for the electron as well as for the hole. So, dj by dx minus C equal to zero and dj by dx minus U is equal to zero for holes also. And when you substitute we get this these 2 equation one for the electron another for the holes and both are on N side.

So, this N subscript n means electron concentration on N side P sub N means hole concentration on N side. So, it is Mu n times n n times d by dx Plus mu n times E times D n by dx and then again the diffusion terms q d 2 n by dx square + G minus R which is minus U is equal to zero. Similarly for holes you have this equation. Now even under bias even under forward bias the carries are getting injected. So, because it is quasi neutral region and there is some excess of these minority carriers entering from the other side accordingly the majority carers have to adjust themselves.

So, it will remain neutral. So, there will be slight change in the major carrier also. So, you can say N n minus N n naught is equal to P n minus P n naught on N side and similar condition will apply on the P side also. So, you can say that the derivative of N and P on N side should be equal to. So, D n n by dx is equal to D p n by dx. So, this is a requirement of the charge neutrality because we have assumed that this region is quasi neutral region.

This region is quasi neutral region then of course we take these 2 equation one and 2 and we try to eliminate these terms by multiplying mu P and P n and mu n N n equation one and equation 2. So, we get rid of this d by dx term. So, this is eliminated. So, we have term in terms of P n minus P naught by Tau P + some coefficient N n minus P n by N n ny mu n + P n by mu n E times D p by dx Plus coefficient da times d 2 x P n by dx square equal to zero.

So, this is basically diffusion equation where this da is basically MV polar diffusion coefficient this complex term and Tau P is basically P n minus P n naught y net recombination rate. So, sometimes recombination rate is represented as P n minus P n naught equilibrium concentration divided by Tau p. So, this is basically kind of carry a lifetime for these holes because holes are minority carrier and they get absorbed because these electrons are made on in majority and on N side.

So, these magnitudes will disappear after some time. So, the time it takes the average time this minority carriers spends is basically Tau p. So, for low level injection where P n is much less than N n so, this equation basically reduces to this d a can be represented by simply mu P because you see here P n is much less than N n. So, you can ignore this P n by dn. So, you have this N n + P n. So, this N n is much smaller. So, P n by N n by D p.

So, this will be simply mu P terms E times D p by dx + da. So, you see here this is P n minus. So, this is N n is last. So, you will just take the N n here and N n by mu P. So, just term u P remains here and for D a you can write in terms of D p because this N n by N n will cancel D p will remain here. So, this is called minority carrier diffusion equation minority carrier diffusion equation.

Similarly we can write on other side also. So, this is equation contains the electric field but we have assumed that the selective field is almost zero here. So, again we can further simplify it. So, under the electric field zero this middle term disappears. So, you have this D p times d 2 by D n square equal to zero. So, this is the simplified equation that we can use inside the quasi neutral region.

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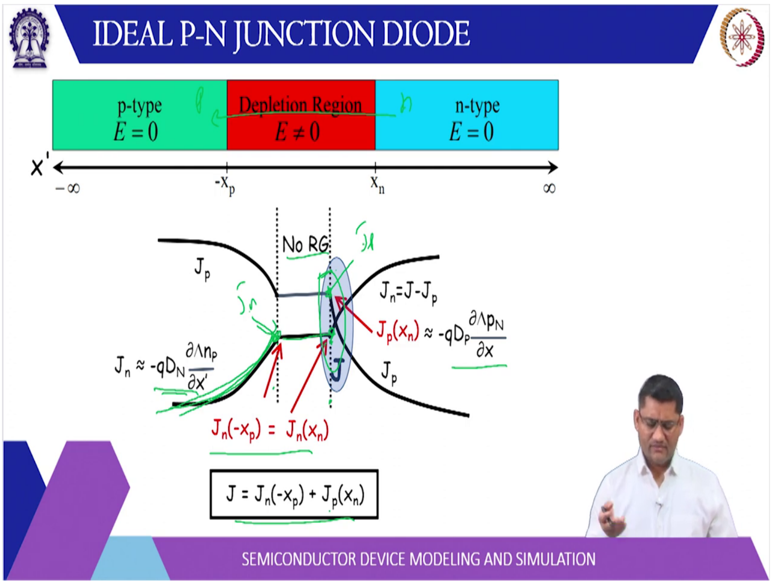

So, when you combine the 2 this is the mind to carry diffusion equation on P side this is a magnetic array division on equation on N side. So, on N side holes are in minority on P side electrons are in minority. So, number of electrons that are injected here less is Delta n number of holes that are injected is Delta p. So, when you solve this equation basically you will get some exponentially decaying terms basically.

So, this let us say here this Delta n is Delta n naught times exponential x by L which L will be D times Tau. So, that is a linear equation you will get exponential equation you will get and if you recall that here. So, these are 2 this is this E F p this is E F n. So, in a region where these 2 different formulas will exist for these different carriers so, NP product is no longer n i

Square because in the same region here there are 2 different are available for different carriers.

So, NP product becomes n i Square times exponential the difference of Fermi level, so, E F n minus E F P by kT. So, that will appear here and that basically tells you and of course in neutral region n p is equal to n i Square and inside the Fermi level this E F n minus F T is actually the applied voltage because we assume that all the applied voltage falls across this depletion region and this is equal to the applied voltage.

So, you can write n p is n i square exponential q b by kT. So, that actually tells you if P is a concentration here. So, Delta n will be given by this equation n i square by P times exponential q b by kT and inside the depletion region again you can write this quantity equation here so D n by dt is dj by dx Plus generation minus recombination. So, generation minus recombination is due to thermal region and it is assumed to be zero here.

So, inside the depletion region dj by dx has to be zero. Similarly for the holes dj by dx has to be zero inside that will is a reason because we have assumed that this thermal generation recombination is zero. So, there is no generation recombination in case of ideal diode. So, using this equation here we can further calculate the carrier distribution. So, what is actually happening so, this is n side this is P side.

So, these electrons are moving here crossing the depletion region inside the depletion there is no can change in the current because there is no generation recombination and once this electron come here they Decay down basically so they diffuse as well as recombine. So, it basically gives some kind of exponential profile and from the exponential carrier profile we can get the current q n times d by dx.

So, derivative of exponential is also exponential. So, this current will also be exponential function of the position and similarly on P side again you will have experiential profile for the holes because they are minority here and the total current you can find out because you can calculate whole current year you can calculate electron current year and this electron current here is same as here because there is no change in the current in the depletion region.

So, at this point you know the current you know the j p here j n here and you add that to you get the total current. So, total current is basically the whole current at depletion region boundary of the entire region then electron current and depletion with depletion region boundary of the entire region. So, total current is basically the addition of these 2.

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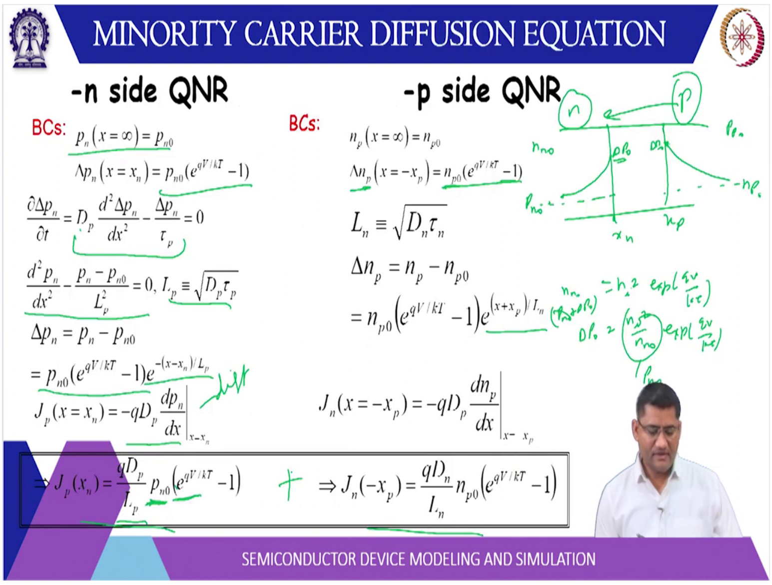

And now that we can easily calculate by solving for the carrier consultation profile. So, what we can do let us draw look at this picture. So, this is a depletion region this is n site this is P side. So, electrons come here let us say this concentration is Delta n zero the hole come here this concentration is Delta P 0. So, P on N site, so, this majority concentration. So, this is let us say majority it is n naught and when it is p n naught.

Similarly majority is p p naught minority is n p naught. So, on the N side multiplication is p n naught and Delta P here at x equal to zero or x equal to x n this is x p is now the product is n i square exponential q v by kT that is PN product. So, n is basically n naught and P is p n naught + Delta P naught. Now this Delta P naught is much larger than p n naught. So, you can ignore it basically. So, Delta P naught is n i Square by n naught times exponential q V by kT.

So, that means Delta P naught is equal to n i Square by n n naught exponential q V by kT. So, this is basically your P n naught the multi carrier or N side. So, that is what is written here. Similarly on P side electron concentration is given by n p naught exponential q V by kT and of course we are taking the difference is Delta n p. So, this is n minus n naught and P minus P naught. So, there is a minus one here which is basically n p naught and p naught we are subtracting here.

Now we know that 2 boundary conditions. So, we can solve this multi carrier diffusion equation D 2 Pi P by dx square minus P by L P Square l P is root d Tau ok. So, this is the multi carrier diffusion equation D tau is written as L P Square and when you solve it you get some exponential x minus x n y l P exponential x + x p by L n and from this carrier concentrational profile by differentiating we can get the diffusion current. So, this is diffusion current.

We have assumed that field is zero there is no drift current. So, only diffusion current is there. So, these are the 2 different current equations. So, diffusion current on N side due to the holes is q D p by L P times p n naught exponential q V y kT minus 1. So, this current actually varies exponentially with the applied bias it is proportional to the p n naught the magnetic carriers. So, that means if a region is less doped then the carriers will be more and then it will have more current flow or you can look it like this right.

Let us say P is highly doped. So, it will inject more number of holes there. So, P is highly told me is this n side is less doped. So, less doped means minority carry concentration is more. So, that is what is actually coming into the picture here. So, whole current density is q D p by L p times p n naught exponential q V by kT minus 1 and the electron diffusion condenser is q D n by L n times n P naught exponential q V by kT minus 1.

So, the total current will be the sum of these 2. Now here we are basically assumed that the length of this region is much larger than the diffusion length. So, L p is a diffusion length if the length is smaller than the diffusion length then accordingly this equation will be modified. So, we will maybe discuss in one of the example.

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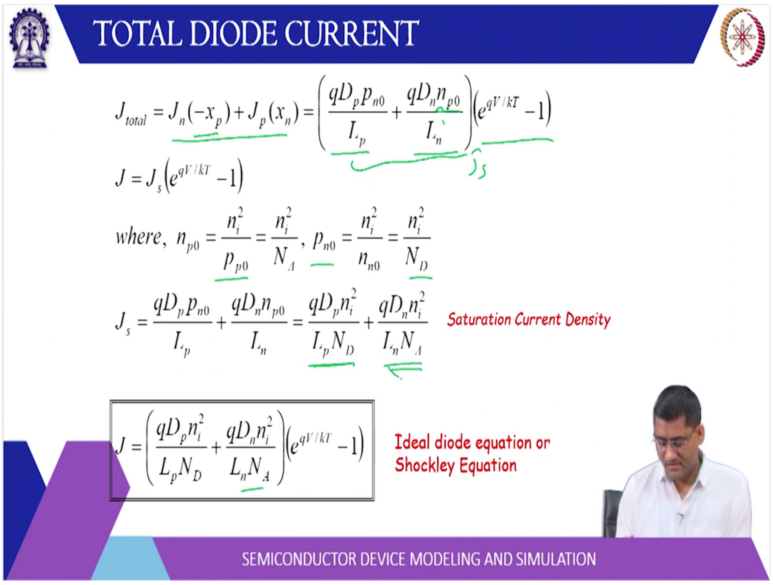

So, the total current is the sum of these 2 currents. So, q D pn naught ny L p + q D n n naught by a l n exponential q V by kT and of course we know n p naught is n i Square by N a and P naught is n i Square by n d. So, we substitute again here. So, this pre factor is called J s or the saturation current density and that is given by q D pn i square by L p and D + q D nn i Square by L times n a. So, it is inversely proportional to the doping on opposite side.

So, you see here this is n this is on N side due to the holes. So, it is n i Square by n D so this is on N side and this n i square by N a on P side and L is root D Tau. So, you can again this is root of D Tau. So, you can also write it as root of d by Tau ok. So, this is a ideal diode equation or is also called Shockley equation.

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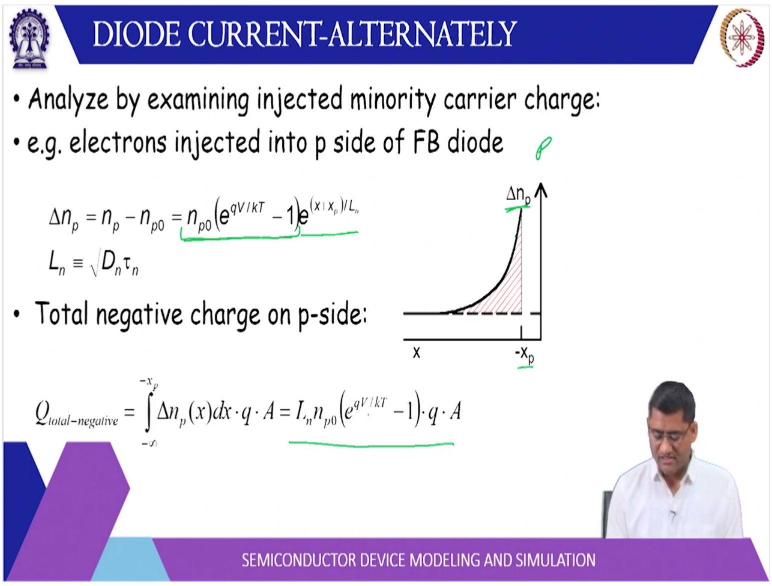

There is another simpler way to calculate this current and that is called basically charge zero charge conservation. So, you can look on let us say on P side. So, on P side these are this is the electron profile that we have calculated that n p naught exponential q by kT this excess number of electrons. So, this is in excess to the actual minority carrier concentration times exponential x + x p by L n.

So, L n is a diffusion length of the holes in ends N region. So, if you take the area of this region there is a total charge. So, that total charge if you integrate from minus x p to Infinity you will get L n times n p naught exponential q by kT minus one times q times a where a is the area of cross section. So, this charge will be there for some Tau time.

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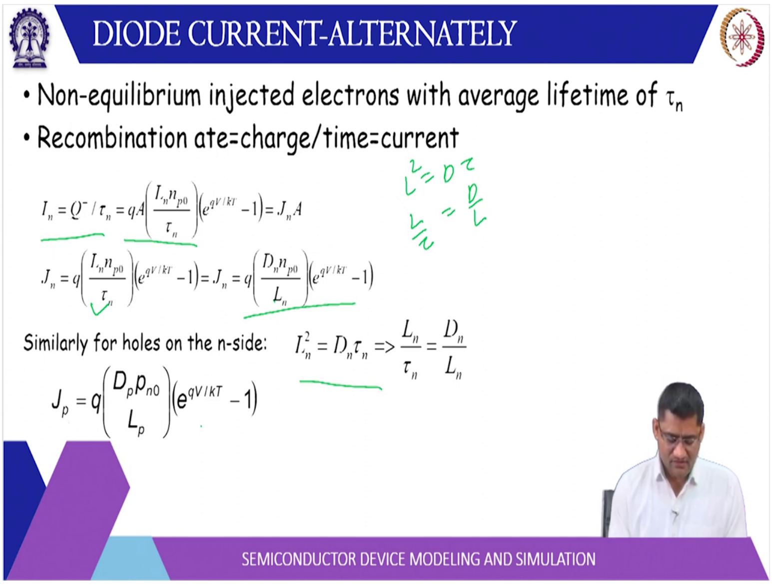

So, if you divide this thing by Tau you will get this expression L times n p naught by Tau. So, L times n p naught by Tau, Tau you can write L can written as D Tau. So, L is equal to D Tau. So, L by Tau can be written as L Square equal to D Tau. So, L by Tau can return as d by L. So, that is what is done here l y tau is written as d by L here and that was expression that we got for from the magnetic by solving the minority carrier diffusion equation.

So, simply for whole side we can also write the similar equation. So, for holes we can write q times d P by L p p n naught exponential q V by kT.

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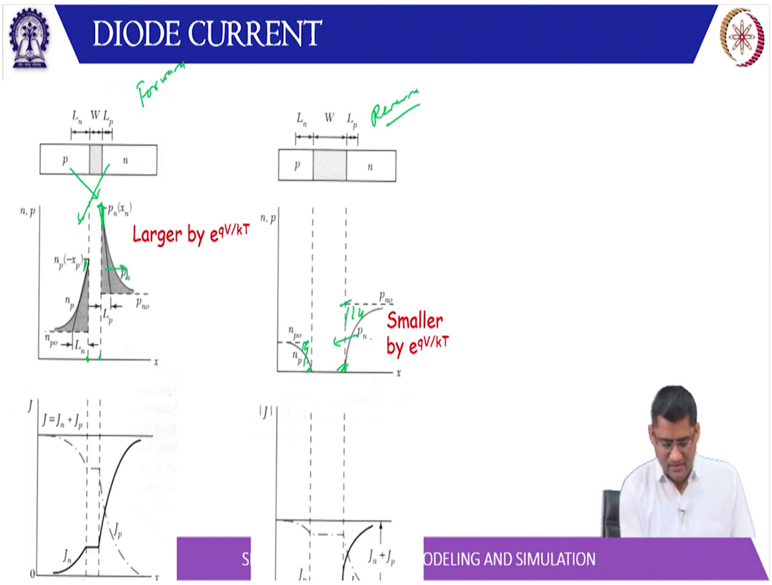

So, they both give rise to the same equation. So, in summary we can write that for a PN Junction when it is forward bias. So, this is the forward bias holes are injected from P side electrons are injected from N side. So, from this you can also tell the whole concentration is large. So, P side is highly doped compared to N side and then there is a you know carrier gradient. So, that tells you the diffusion current the slope at this boundary of the depletion region.

The slope at the boundary of wiser region these 2 current add up and give you the total current and in case of reverse bias again this same expression is valid exponential q V by kT but now voltage is negative. So, this basically when voltage is negative this term will be almost zero. So, this difference will be minus one. So, that means the difference is now Delta P is minus one. So, this goes to almost to zero here and Delta n is almost zero. So, it goes to zero here.

So, this is called carrier depletion. So, they are depleted of carriers here they are depleted of care carriers here. So, that means carries are even smaller than the minority carrier concentration. And in this case also the current will be you know negligible in case of reverse bias and the component will be there. So, here the diffusion will be something like this. So, these holes are diffusing from N side to P side.

So, this diffusion is due to the minority carrier earlier diffusion was from left to right. Now it is right to left for the holes so, because this number of carries are small here. So, this current will also be small.

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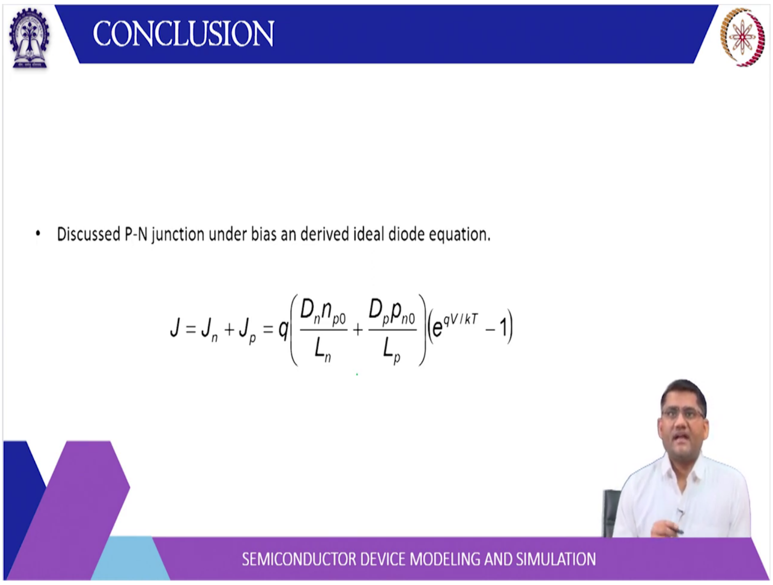

So, in summary we have discussed the PN Junction under bias and we have derived the IV relation for a ideal diode that is written by J the current density is q times D n n p naught by L n + D P naught by L p times exponential q V by kT minus one. And if you notice this for one sided Junction let us say if once that is highly doped then for highly doped site let us say N is highly doped then P will be very small. So, this will be negligible.

So, the mainly the current will come from other side so that means if this P is Allied out P +. So, there will be large flow of holes here and a small flow of electrons here. So, mainly this contribution will dominate. So, that you can see from this equation also, thank you very much.