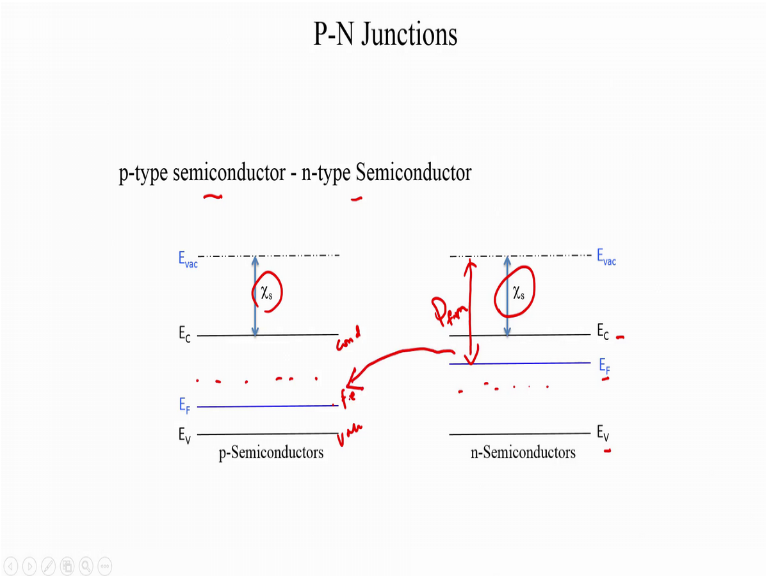
Semiconductor Devices and Circuits
Prof. Sanjiv Sambandan
Department of Instrumentation and Applied Physics
Indian Institute of Science, Bangalore

Lecture - 25
PN Junctions: Electrostatics

(Refer Slide Time: 00:15)

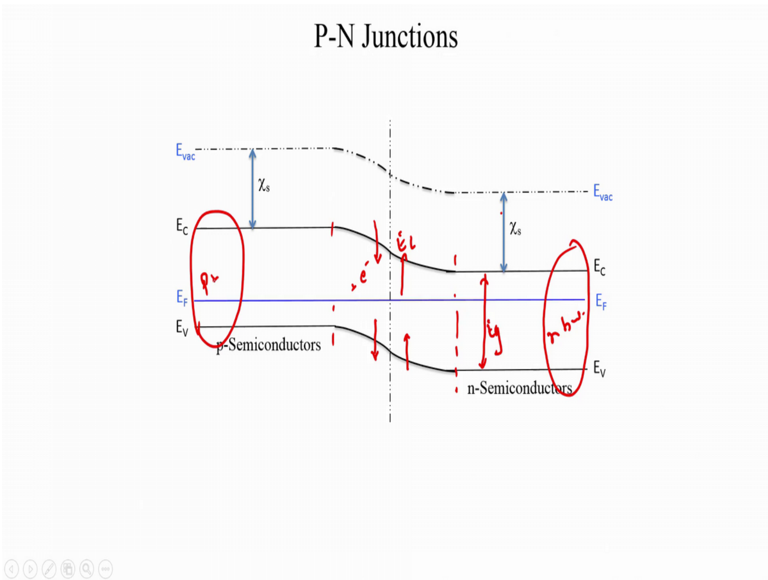


So the next topic we will get into discussing is something called as a PN junction. And it is also a junction that we sort of looked at earlier on when we just you know when we discuss the concepts behind how to create band diagrams etcetera. As I mentioned the PN junction is actually a junction created between a p type semiconductor and an n type semiconductor. Now if the semiconductor is the same you will end up with two these two materials having band diagrams of this kind. So, you have your conduction band edge, you have your valence band edge and since it is a p type material you have a Fermi level that is located slightly below the intrinsic Fermi level and this depends upon the doping density.

And in the case of an n type semiconductor you have your valence band, your conduction band and you have a Fermi level that is above the intrinsic Fermi level position. Now since the semiconductor is the same your electron affinity is also the same. So, if you were to create a junction between these two semiconductors if you if you remember if you recollect the idea behind drawing band binding diagrams we need to understand how the electrons would flow.

So, in this case the Fermi level here for the n type semiconductor is higher than the Fermi level position for a p type semiconductor. And therefore, which basically implies that the work function of the n type semiconductor is smaller than the work function of a p type semiconductor therefore, the electrons will flow from the n side to the p side.

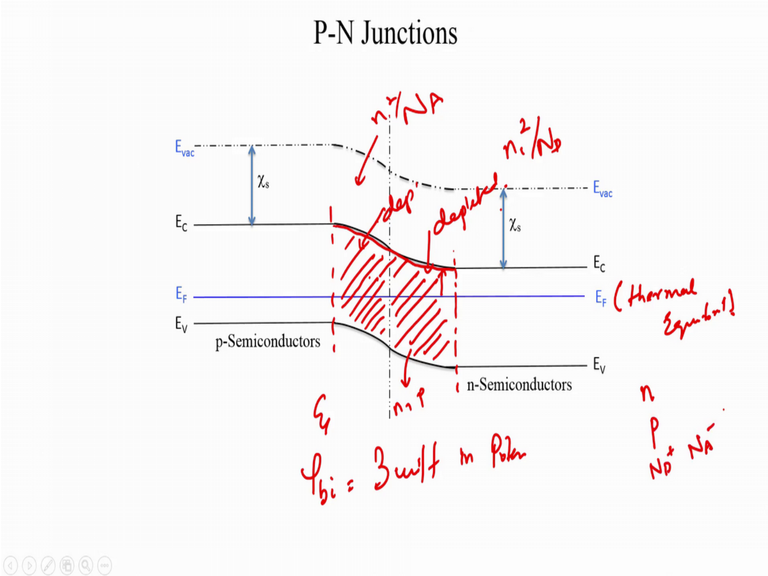
(Refer Slide Time: 02:00)



And therefore, if you have to construct this junction, what we will see is that in the n type material near the junction; the junction is lost electrons and therefore, the conduction band edge moves away from the Fermi level. Whereas, the valence band edge moves towards the Fermi level whereas, in the p side the interface is gained electrons. So, you have added electrons to the p side and therefore, the conduction band edge moves towards the Fermi level while the valence bandage moves away from the Fermi level.

Now throughout this band bending diagram your energy gap is more or less constant, your electron affinity is constant and far away from the interface that is very far from the junction the semiconductor really does not notice any effect of the other type of semiconductor or the effect of the junction. And therefore, you have your typical n type bulk material and your n and your p type bulk material. So, this is the PN junction diagram the PN junction band bending diagram. So, the Fermi level is aligned as is required for at thermal equilibrium.

(Refer Slide Time: 03:15)



So, this is true only at thermal equilibrium and you have this kind of a band bending diagram and just as in the case of metal semiconductor junctions, we can define the electric field in this region, we can define something called as a built in potential that is effectively the potential difference between due to this band bending ok.

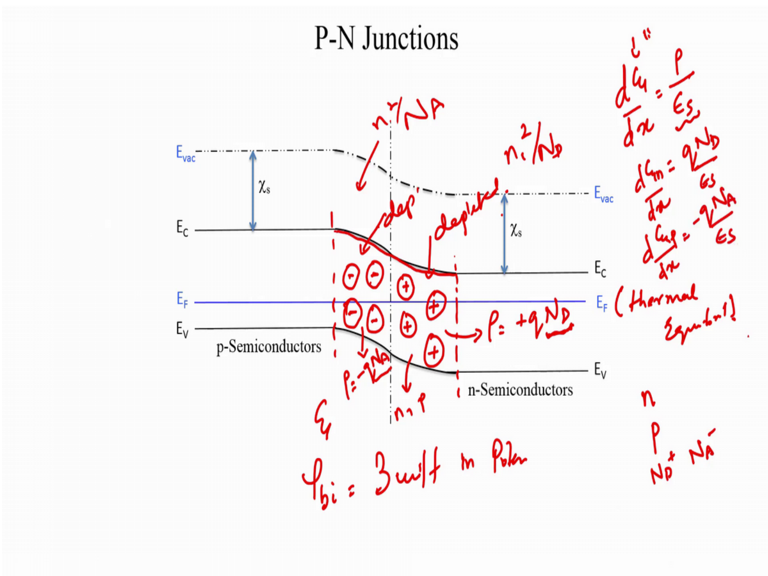
So, that is the built in potential and now we will we will try to use Poissons equation, to try and understand what the electric field is and what the built in potential is. And that will be the first you know exercise we will go through and we will also define some coordinates because these regions near the interface ok. If you look at this, let me just draw a dotted line here and a dotted line here. Now if you think about this region on the inside it has lost electrons and on the and it did not have many holes to begin with.

So, in some sense this region is depleted of free carriers and on the p side it has gained electrons which would have recombined with all the holes. Because you have it had a lot of holes, but since these electrons have come in, the holes and the whole population is also cantina ok. If you want you could think of it as the holes have been diffused to the n side and the electron population was not very large to begin with. Because here the whole population was approximately n i square by ND and there the like the electron population was ni square by NA. And therefore, those numbers not very large to begin with and therefore, this region is also depleted.

So, everywhere you see a band bending you could say that the region is devoid of free carriers. Now in reality it is not completely depleted you do have free carrier concentration and the electron and hole concentration can be identified by looking at the difference between the Fermi level and the conduction bandage or the Fermi level and the valence bandage respectively. But if you assume its depleted it makes you know your solution for the electrostatics a lot simpler and we will start with that assumption ok.

But in the metal semiconductor junction when we already looked at a very general Poisson equation wherein we considered the electrons we consider the whole population, we considered the dopant ions and we did solve Poissons equations you are already familiar with what to do if you have to consider everything. But for the case of for this analysis, so we will just assume it is a depleted region.

(Refer Slide Time: 06:20)

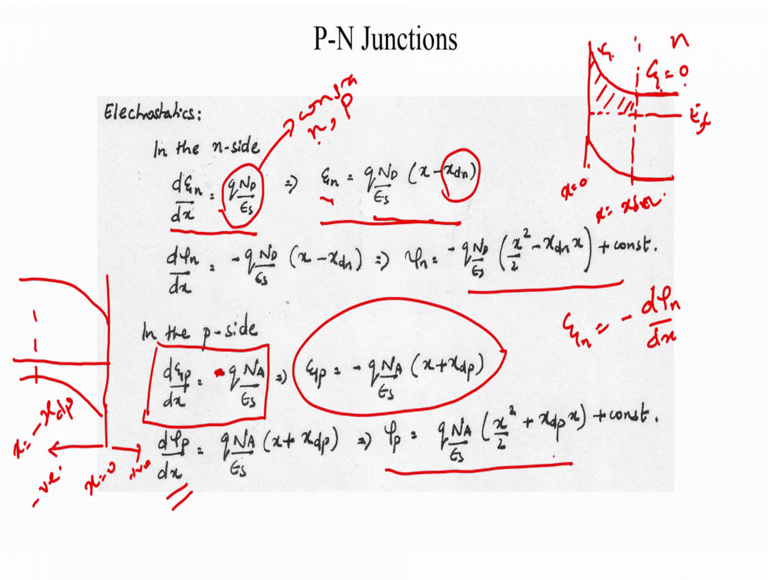


So, if it is depleted what is the charge concentration on the n side you have all the positively charged fixed donor ions ok. So, these had donated electrons to the n type material and those electrons have all diffused onto the p side and therefore, these are fixed donor ions. And on the p side you have the negatively charged fixed acceptor ions. So, these are the acceptor dopants that gave up or that took an a electron and essentially gave up a hole and those holes have now diffuse to the n side and therefore, you have exposed acceptor ions.

So, this is the situation you have a depleted region where you have a charged concentration here, which is basically plus q ND where ND is the number of dopants per unit volume. And the charge concentration in the p region is minus q NA where NA is the acceptor number of acceptor ions per unit volume. So, if we have to write Poissons equation for the n and p side what would it be. Poissons equation tells you that d by we looking at only one dimensional cases here. So, de by dx where this is the electric field is equal to your charge concentration by epsilon s where this is the permittivity of this semiconductor.

So, the charge for the n side your Poissons equation is going to be de n by dx the subscript n is to denote the n side is equal to your charge concentration on the n side which is q ND by epsilon s. And for the p side you have a Poisson equation which is d e p by dx is equal to minus q NA by epsilon s. So, this is the these are the equations that we need to solve to understand the electrostatics.

(Refer Slide Time: 08:27)



And what we will do is we will solve for the n and p side separately. So, on the n side you have your Poisson equation as this, which is quite straightforward because this is a constant ok. And it is a constant because we have not assumed we are not consider the n and p the free carriers. And therefore, the electric field is simply given by this term here and you will already recognized that the boundary condition has been applied ok. And what was the boundary condition; since on the n side if you only look at the n side we can draw the band bending diagram as this ok.

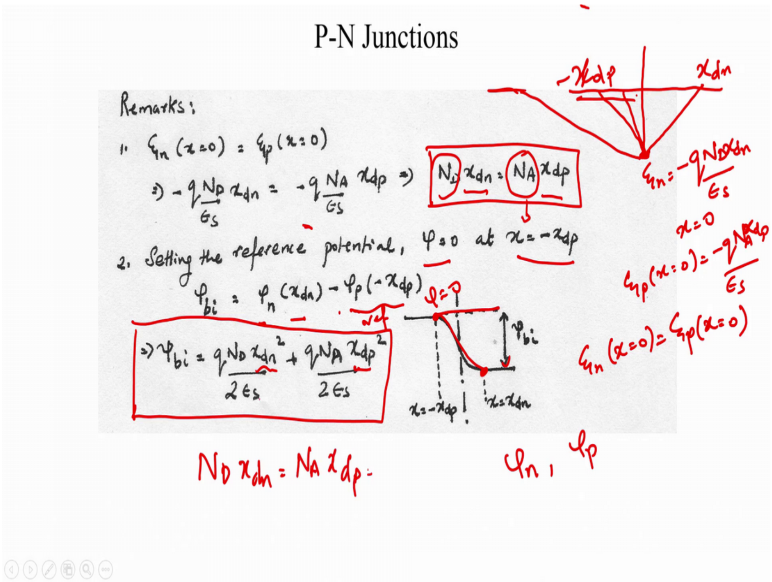
So, that is only the n side of it and that is your Fermi level. And we say that at x equal to xd n all the band bending has stopped and the bands have now become flat. And therefore, at this edge the electric field is 0. And its only within this region from say x equal to 0, which has been defined at the junction to x equal to xd n that you have any electric field.

And if you say electric field is 0 at x equal to xd n then you have apply is boundary condition to this to the solution and you end up with the electric field being this particular term here. And the potential if you look at the potential, since the since the potential since the electric field is nothing, but the derivative of the potential is a negative of the derivative of the potential you can now find the potential function as well which is which is going to give you a quadratic relation of this kind.

Then on the p side you have your Poisson equation to be defined by this expression where this is the charge concentration NA is all negatively charged ions and therefore, you have a negative sign. And you apply the boundary condition if you look at the p side you sorry you have a band bending that looks like; that looks like this ok.

Let me just be a bit more accurate that looks like that and on the p side since this is my x equal to 0, we have band bending till a point of x is equal to minus x dp ok. So, this side of the axis is all negative values of x and that is all positive values of x. And you apply that boundary condition and you will end up with this solution to your electric field and now you can go ahead and calculate the potential. So, the expression for the potential would be another quadratic which is telling you what is the potential on the p side.

(Refer Slide Time: 11:31)



So, since there has to be a continuity in the electric field now we have solved for the electric field on the n side and the p side separately right On the n side we got an expression which was q ND by epsilon s into x minus x tn which means at x equal to 0 my electric field is negative. So, en is negative and it says it is minus q ND x dn by epsilon s. So, that is my electric field on the n side at x equal to 0. And if you use the expression for the electric field in the p side if you substitute x equal to 0, you end up with an expression of ep at x equal to 0 is minus q NA xdp by epsilon s.

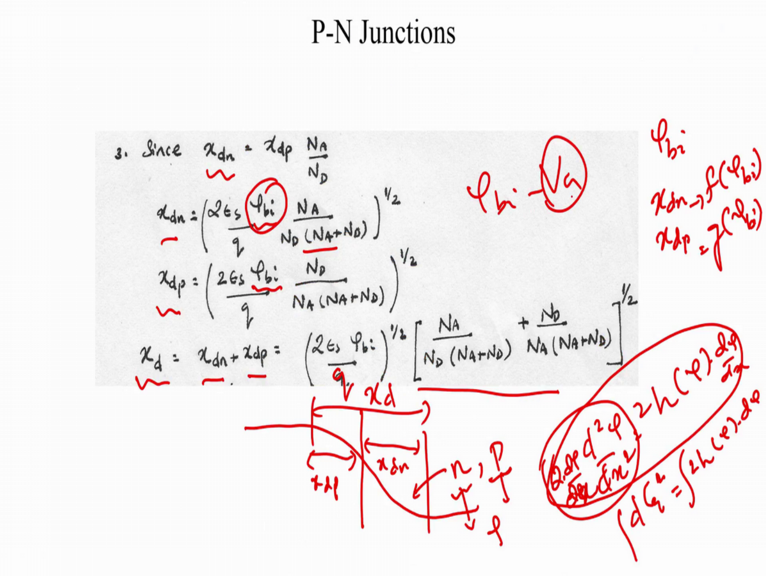
Now, we are talking about the same field for the field has to be continuous. So, you have an electric field that varies like this and varies in this manner with that being your xdn and that being your minus xd p. So, since at x equal to 0, en has to be continuous you have en and x equal to 0 being your ep at x equal to 0, which gives us a very important relation that your ND into xdn must be equal to NA into xdp.

So, what is this relation mean intuitively it means that, if my charge if my dopant concentration is large let us say NA is much larger than ND it says that xdp is going to be much smaller than xdn, which means it takes a lot less distance for me to shield all the field ok. Because my charge concentration is very large, I just need a smaller amount of charge exposed before all the electric field is nullified.

On the other hand if my charge concentration is very low I need to expose a lot more charge before the electric field is nullified. So, that is essentially what this expression intuitively implies. And now we also know the potential at in the n side and on the p side from our Poissons equation. See if we set a reference potential so, let us say we set a reference potential at x equal to minus xdp you could set a reference potential anywhere, but we say that this point has got a potential of 0. And therefore, this entire potential difference between here and x equal to xdn is my built in potential.

So, that potential is my phi n at xdn minus phi p at minus xdp which is my reference, so that is my reference potential. And you substitute for these two values of x, you say x equal to xdn there and you say x equal to minus xdp here and you solve for the potential and you calculate this difference and you will end up with this expression for the built in potential. So, it depends on the square of xdn and xdp ok. So, this is a bit about the electrostatics of your PN junction which is obtained from your Poissons equation.

(Refer Slide Time: 14:59)

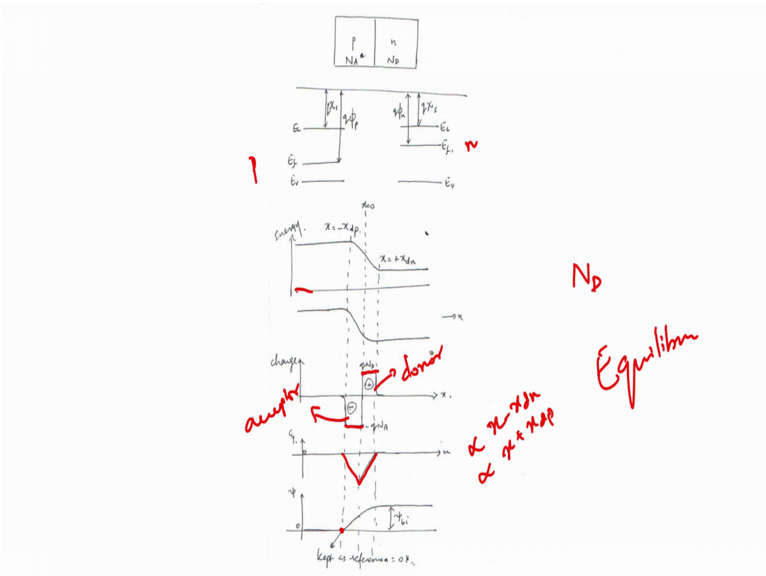


Now, taking this one step further, so that is my potential term right, but we already know. So, let us make use of point number one in this expression that is ND into xdn is equal to NA into xdp so let us make use of that.

Since we already know that we can write your xdn in terms of xdp alone or vice versa. And using that in your potential expression using that in your expression for phi bi we can estimate what xdn and xdp are in terms of phi bi you will find that your xdn is got this dependence on the built in potential, and your xdp has got this dependence on the built in potential. And therefore, the total depletion width that is taking into account the p and n side the total depletion width that we call as x d is equal to xdn plus xdp. So, that is your xdn that is xdp and this sum is simply the sum of these two terms and you end up with this expression.

So, these are all very useful expressions for you to perform quick calculations ok. So, even though we have not made we have assumed that these regions are deplete devoid of free carriers we did not take into account n and p because if we do take this into account these will all be functions of the potential. And therefore, your Poissons equation will have a nature of this kind it will be you know some function of the potential.

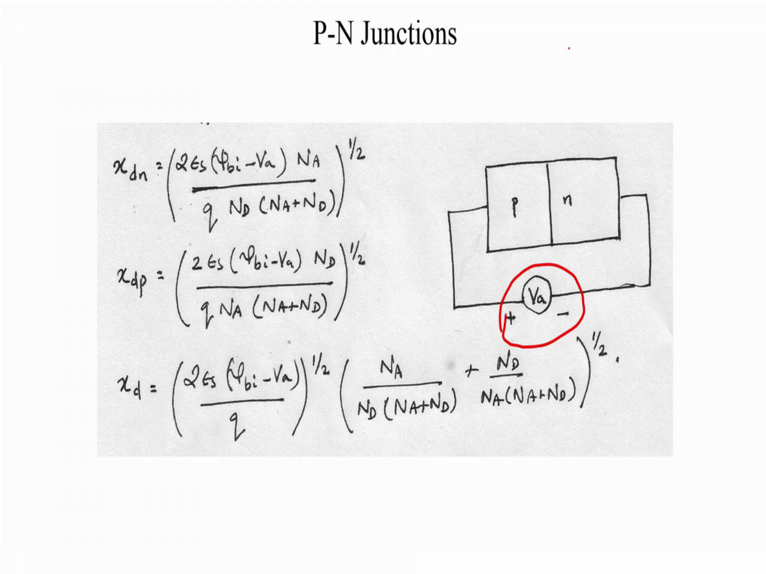
(Refer Slide Time: 16:43)



So, just to summarize what we looked at in the electrostatics do forgive me if this writing is too small, we saw that this is the n side and that was your p side. And once the junction was created you have a band bending diagram that looks like this and if you look at the charge profile versus distance you have all the exposed donor ions exposed there and you have all the acceptor ions exposed here. And since our donor dopant concentration was constant right it was not varying with space this is constant with space and that is constant with space.

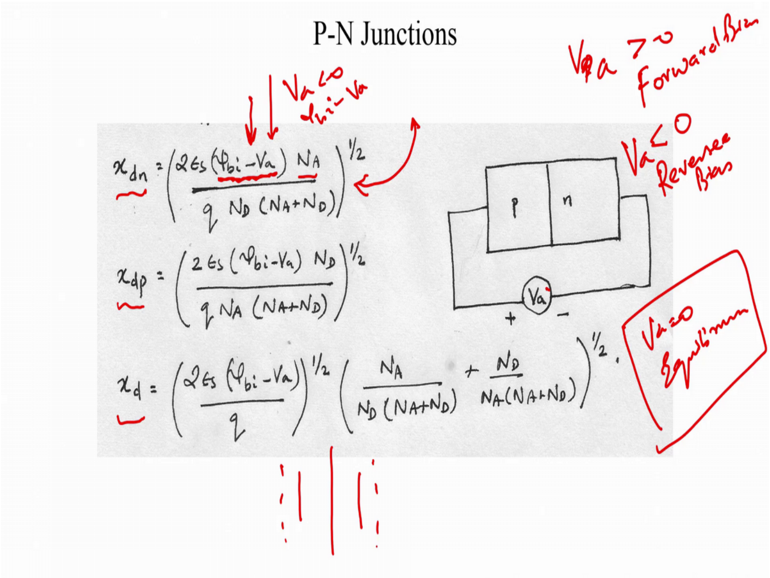
And the electric field profile looked like this, we saw that it had a relation of x minus xdn on the n side and is proportional to x plus xdp on the p side with x being a negative term. And if you looked at the built in potential, we had set this as a reference of 0 and the built in potential slowly increase as you went from the p to the n side. So, this is a summary of the electrostatics of a PN junction. So, now, let us look at the current voltage characteristics and before we do that, we need to see what happens when we take the system out of equilibrium. So, this is all at equilibrium it is only at equilibrium the Fermi level aligns when you create a junction.

(Refer Slide Time: 18:17)



So, when we take it out of equilibrium let us do so by applying a voltage ok, so we are going to now apply a voltage across the PN junction. And the voltage is being applied in a manner where the plus is toward the p side is at a higher potential as compared to the n side; if the voltage on the p side or you know as we have drawn this picture if my Va is greater than 0.

(Refer Slide Time: 18:43)



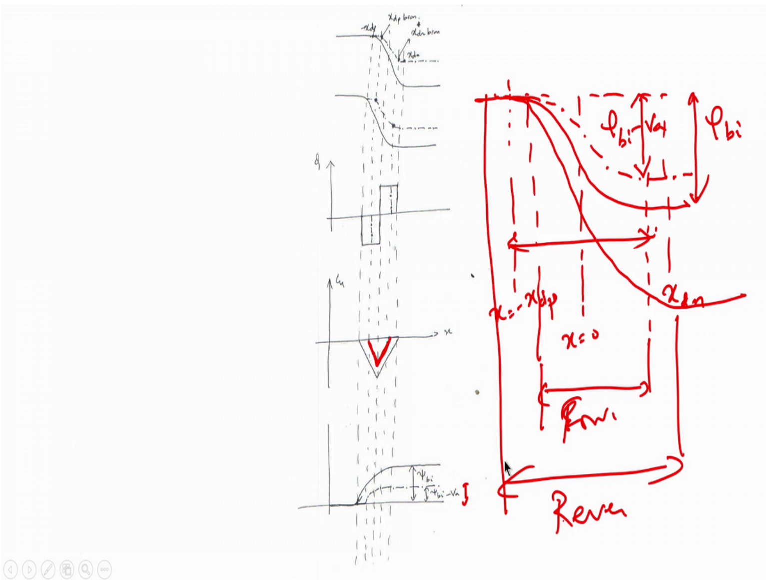
That is the voltage on the p side is greater than that on the n side then the device is supposed to be in forward bias, and if the voltage is less than 0 then the device is said to be in reverse bias, and if the voltage is equal to 0 then you are at equilibrium.

So, everything we have discussed so far is all at equilibrium there was no voltage applied or in other words you know Va was equal to 0. But now when you start applying a forward bias or a reverse bias that you would start taking Va to be nonzero then your built in potential changes a little. And we have already looked at it in the metal semiconductor junction you see these relations are quite familiar a quite similar to your metal semiconductor junction relations except for the fact that you have here you have both an NA and ND doping etcetera, but you will see that all the other terms are quite they are quite familiar ok.

So, just like in that case you can take an intuitive leap by noting that your built in potential term will now at equilibrium instead of using the equilibrium value we replace that with phi bi minus Va in order to calculate your new xd n and your new xdp and your new xd. So, instead of just using phi bi instead of just using phi bi we replace that with phi bi minus Va where Va is the applied voltage in order to get your out of equilibrium values.

So, which means what? Which means that when my Va is positive my xd decreases, both my depletion widths the xdn and xdp decrease and my total xd decreases. And in reverse bias when my Va is negative if Va is less than 0 then phi bi minus Va is going to be a larger number and my depletion widths would increase.

(Refer Slide Time: 21:02)

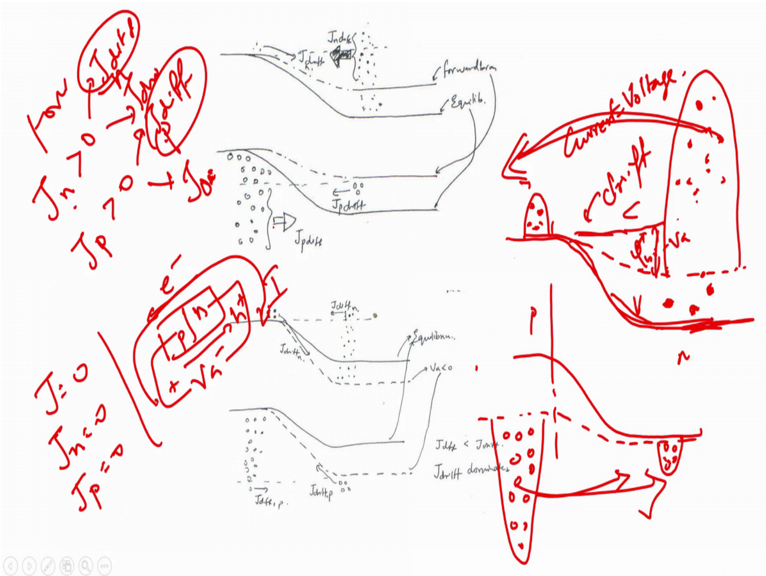


So, to give you an intuitive feel again just to summarize what non equilibrium does, so let us say let me sort of draw this much more clearly. So, let us say that was my equilibrium case that is the band bending in equilibrium. So, that was the value of xdn, so let us say my x equal to 0 is somewhere here and that is my x equal to minus xdp and that was the built in potential right there so this is all at equilibrium. Now when we shifted out of equilibrium the band bending changes a little. So, you firstly make the bands a little bit more shallow, because the built in potential will now become phi bi minus Va.

So, in forward bias the band bending will be a little shallower and the depletion region is only going to be extending from here to here it is not going to be as large as before its going to be much smaller. And on the other hand if it is a reverse bias, if its reverse bias the band bending will be a little bit more steeper, because my phi bi is increased and it will also extend to a larger distance ok. So, that is going to be the reverse bias case that is going to be the equilibrium there is going to be the forward bias case and that is going to be the equilibrium case.

So, that is sort of intuitively summarized and if you look at the electric field profile in forward bias it is going to be something like this. Because the depletion widths are now reduced and the built in potential and forward biases of course, going to be less, it is going to be phi bi minus Va and in reverse bias it is going to be larger because your Va is negative.

(Refer Slide Time: 23:13)



So, now let us start heading towards understanding the current voltage characteristics. So, what defines the current voltage characteristics in a PN junction, so at equilibrium so let me just draw the equilibrium band bending diagram.

So, if you think about the n side it has a lot of electrons so that is my built in potential there has a lot of electrons and I will just, in a very poetic manner let me just show you all these electrons is a big heap of electrons there and it is got very few holes ok. So, these are all just holes, but in a lot more electrons and these are all sitting there on the other hand the p side has got a lot of holes we need to mark these differently. So, the electrons are all marked as solid solid objects and the holes are all these hollow circles it has got a lot of holes on the p side has got a lot of holes and very few electrons.

Now, if you look at the electrons in the n side they are trying to climb up the hill ok. If you look at this if you look at the band bending, if you recollect the band bending diagram is all drawn in a manner, where you know it is easy to understand the motion of the electron and hole the electrons like to run downhill the holes like to run up the hills and you know if you increase the potential the energy levels go down and if you decrease the potential energy level goes up ok.

So, that is the way you imagine the band diagram. So, these electrons on the n side have to overcome this barrier they don't they don't like they don't they have to overcome this barrier in order to get to the p side on the other hand the electrons in the p side will just try to run down the hill towards the n side. So, the electrons in the p side will try to drift down whereas, the electrons on the n side have to diffuse across and they can do. So, only if there; there are larger number of electrons you know sitting above this barrier very intuitively, and it is a similar idea on the pisa or if you look at the picture of the holes.

So, essentially at equilibrium there is no current the electron current is 0 the hole current is 0 and the total current is 0 that is because the electrons that are drifting towards from the p to the n, and the holes that are drifting from the n to the p are balanced by any diffusion of electrons from the n to the p and any diffusion of holes from the p to the n. So, all these currents are essentially 0, but the moment I reduce the barrier height, so let us say we apply a forward bias and we reduce their barrier height.

So, let us sort of redraw this picture the moment the band bending shifts to a shallower built in potential. So, by applying forward bias this heap of electrons now protrudes significantly above this much lower barrier height and a lot of electrons start diffusing from the n to the p side.

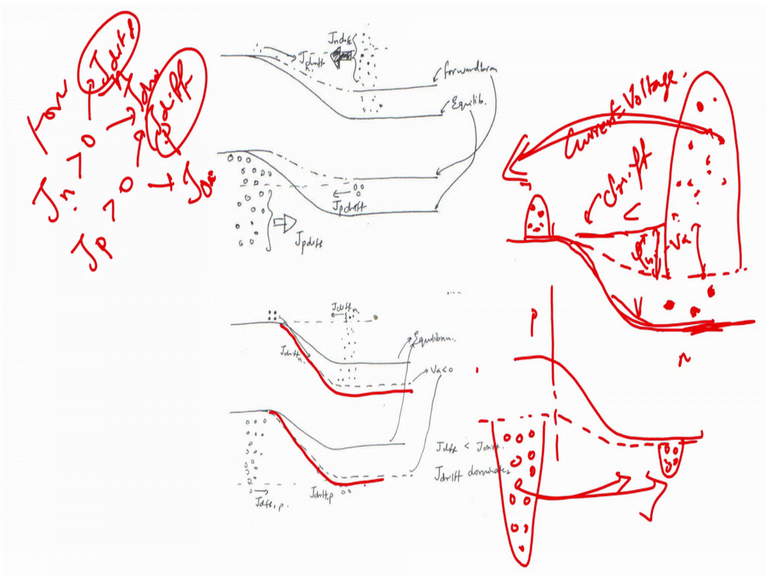
On the other hand the drift of electrons from the p to the n side does change, but the change is not that significant and therefore, the current is heavily dominated by the diffusion of electrons from the end to the p side and the diffusion of holes from the p to the n side. So, just like the barrier height was lower than the conduction band that barrier height is also lowered on the valence band and you have a new picture of this kind.

So, you have a lot these holes now have to diffuse across this much lower barrier and therefore, the diffusion of the holes increases ok. So, you will find that in forward bias the electron current goes to greater than 0 and this electron current is composed of diffusion and drift and it is a diffusion component that dominates.

Similarly, the hole current goes to be greater than 0 and it is the diffusion of hole diffusion of holes that dominates the drift has not changed too much. And therefore, the in effect what this implies is the as a huge amount of transfer of electrons from the n to the p side and holes from the p to the n side. And since we had bias star PN junction in this manner wherein the voltage is positive here and its negative is in the n side which means its forward biased. You have a lot of electrons moving here you have a lot of holes moving this side which means you have an effective large effective current going from the positive terminal of the battery through the PN junction to the negative terminal of the battery.

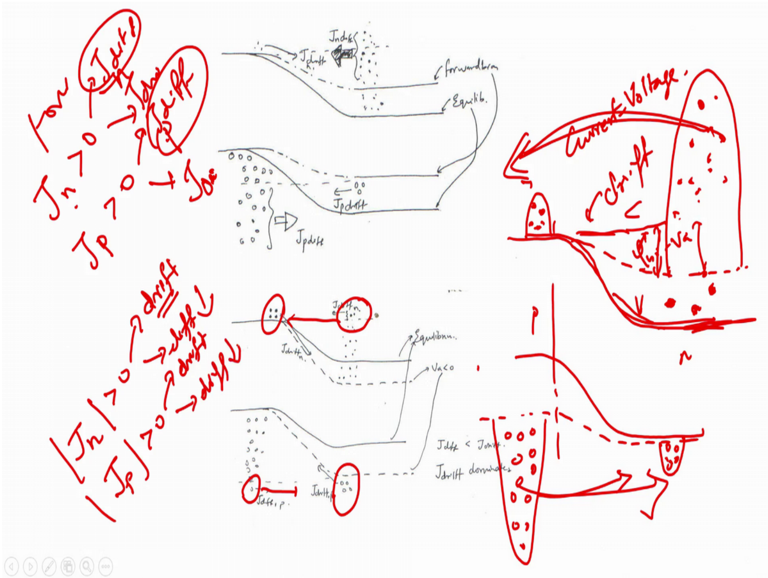
So, it is a very large current that goes through and a small increase in Va reduce the barrier height a little, but since the diffusion component or the you know the electron populations exponentially dependent on the voltage. You find that the electron population scales are much large it scales up very rapidly as you change the value of Va therefore, the diffusion is quite a powerful component in the current. Now on the other hand if you say let us not apply forward bias lets apply reverse bias which means that my Va is negative and the n side is got a larger potential is compared to the p side.

(Refer Slide Time: 29:29)



Then in that case the band bending will become much more steeper.

(Refer Slide Time: 29:37)

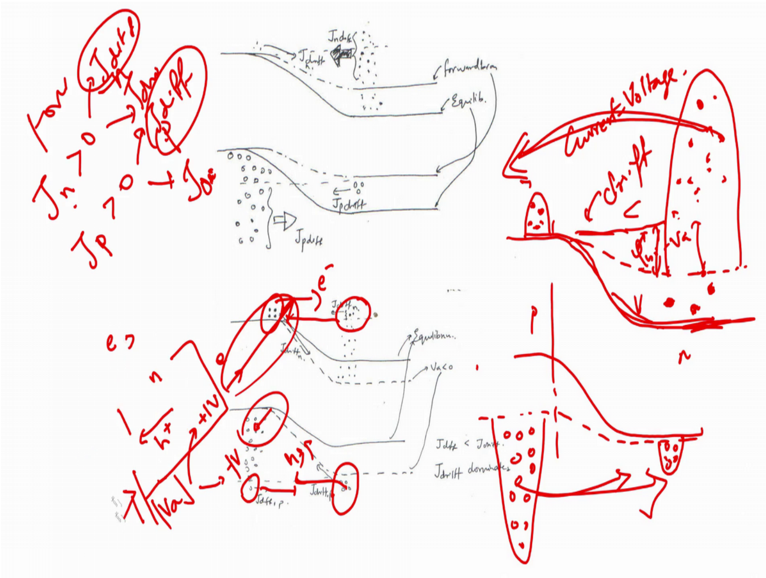


And there will be only few electrons peeping up only few electrons refusing from the n to the p side and very few holes diffusing from the p to the n side.

Whereas the drift once again has not changed too much, but it has definitely been impacted and you will find that the drift current dominates.

The magnitude of Jn is still greater than 0, but it is the drift component that is important now the diffusion component is not so important. And similarly for the p side the drift component is important, but the diffusion component is not important because you have now increased the barrier height by applying a reverse bias. So, what does electron drift do since the electric field is now become larger because of the because of the reverse bias.

(Refer Slide Time: 30:33)



You will feel you will find that the electrons drift from the p to the n side and the holes drift from the n to the p side and that is the current that is important. So, it is this is the scenario you have your PN junction, you have a voltage source that is now negative. So, let me put a negative sign than positive or maybe I should just retain the old convention and just say Va is less than 0 ok, which effectively implies that side is a negative and this side is a positive ok.

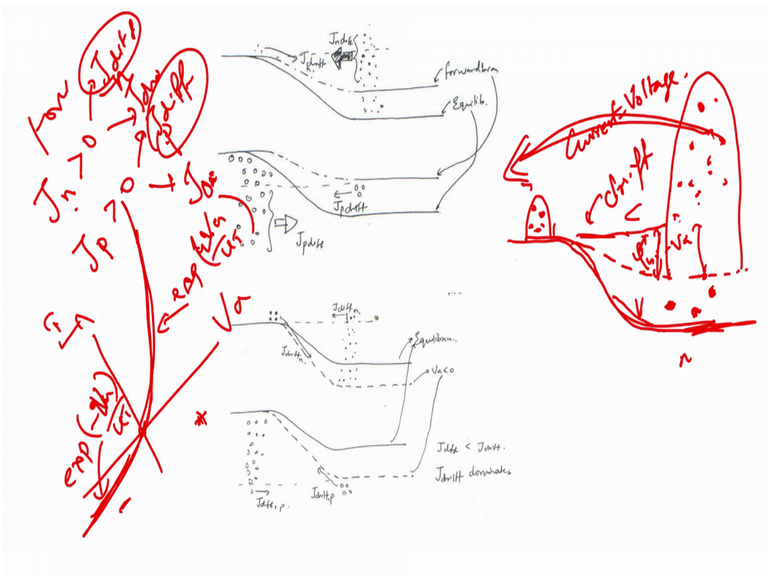
Or once again you know let me just make it just to make things very clear let me apply a battery like that ok. So, that is holes everything and you find that the electrons drift from the p to the n side. So, that is my current and I have holes drifting from n to the p side which means that you have a current flowing this way from the n to the p ok.

And that is my effective current and the PN junction and this current is not very large it is not as prominent. So, if I were to apply the same amount of forward and reverse bias, if I say that the magnitude of Va is same and in one case I apply let us say just for the sake of example, let us say I apply plus 1 volt, the other case I apply minus 1 volt yes I will have currents in the forward and reverse direction.

But the forward direction current will be much larger because the electron population scales exponentially whereas, here it is only the field that is determining the current it is a drift current. And therefore, the forward bias current at 1 volt will be much larger than the reverse bias current at minus 1 volt ok.

And we were sort of mathematically now you know sort of bring an all these arguments all these qualitative arguments in the more mathematical description. In a manner which is quite similar to what we did for metal semiconductor junctions, but we will just look at some of the important differences between the metal semiconductor schottky junction and the PN junction diode ok. So, 1 point which is obvious from what I told you, but this, but needs to be mention this.

(Refer Slide Time: 32:51)



Since the current in forward bias is going to be much larger than the current in reverse bias you do have a rectifying nature for the PN junction. So, you will find that the current voltage characteristics for a PN junction looks like this wherein my bias goes to be greater than 0. The current scales quite rapidly it is an exponential dependence on the voltage and when it is less than 0, it is still an exponential dependence the voltage, but its exponential of a negative negative term.

So, it is going to be dependent on this term there and dependent on this term here and we will see this come out in the mathematics of it ok. So, therefore, the diode rectifies it is got a rectifying property it allows current in one direction, but does not encourage current in the other direction while although it does allow that current ok.