Electronic Materials Devices and Fabrication
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Lecture - 15
PN Junctions under Bias

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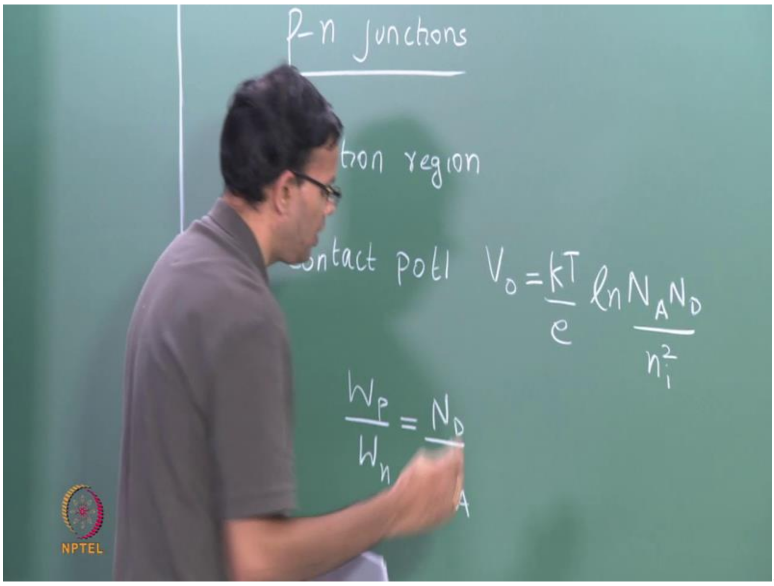

Let us start with the brief review of last class. Last class we started looking at P n junctions. A P n junction is found by combining a P type semiconductor and an n type semiconductor. So, we said that these junctions are ideal. So, that there are defects and both the P and the n type are from the same material. So, you could have a junction between P type silicon and n type silicon. When we form a P n type junction we found that electrons from the n type move to the P type. Holes from the P move to the n and they can re combine. So, that we have a depletion region.

We also found that because these electrons and holes re combine they leave behind positively charged donors on the n side, negatively charged acceptors on the P side. So, that there is an electric feel and n contact potential between the junction. So, we also calculated this value of the contact potential from last class. We naught where n a and n d are the concentration of acceptors and the donors on the P and n side. We also found that the width of the depletion region was inversely proportional to the concentration of your do pens.

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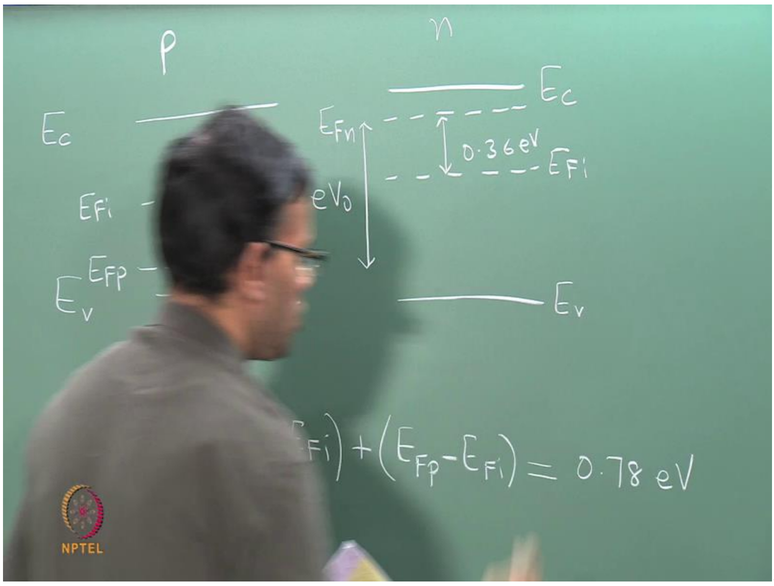

So, that w P over w n equal to n d over n a. So, today we are going to continue to look further at P n junction, but we are going to consider cases when the bias the junctions. So, we will looks at both forward bias and reverse bias. Before we do that I want to link P n junction to the energy ban diagram in the case of a semiconductor. So, let me go back to the example that we look last class. So, we had P n junction with the material being silicon. So, n i for silicon is 10 to the 10 per centimeter cube.

We said that we had P side with an accepted concentration of 10 to the 17 and we have an n side with the donor concentration of 10 to the 60. So, last class we calculated the contact potential in this case. And when we substitute the values we get v naught to be 1.7 8 volts. So, what a want to do is to link the contact potential to the location of the firmly levels and P and the n side. So, let us considered the P side separately and the n side separately.

So, let me draw them here. So, this is my P type and it is my n type. There both silicon ban gap is the same. So, what I want to do is to put the firmly level on the P and the n side. To calculate the position of the firmly level we go back to the formula that we used in the case of extrinsic semiconductors. So, E of P minus E of i is minus is minus k t lawn of n a over n i. So, if we do the numbers this is equal to minus 0.42 electron volts. So, in the case of a P type the firmly level is located minus 1.42 electron volts bellow the intrinsic firmly level.

For just for simplicity I will take the intrinsic firmly level to be exactly ban gap. In the case of silicon this is naught entirely true to be slightly shifted because the effective masses naught the same, but for all practical purposes it is very close to the center of the ban gap. So, E f i is 0.5 5. So, E f P we can get by substituting the value of E f i. So, of an mark it here E f i is the center, E f i is the center and E f P which is the firmly level on the P type is 0.42 electron volts bellow E f i. We can do the same calculation for the n side if we do the numbers, E f n minus E f i k t lawn instead of n a it will be n d over n i.

Once again we can substitute in the values, we get this to be 0.36 electron volts above the intrinsic firmly level. So, in this case E f n 0.3 6 volts. So, when bring my P and n type semi conducted together, I know that the firmly level is liner. So, we can either say that the P has shifted up for the n has the shifted down and this shift is equal to the distance between the 2 firmly energies. So, this overall distance is nothing but my contact potential E v naught. And if we look at the E v naught is E f i oh sorry E f n minus E f i is E f P 5.

So, that this entire distance which is equal to 0.78 electron volts, which gives you v naught to be 0.78 volts which is the same value that we calculate from the formula. So, the contact potential nothing but the difference between the firmly levels on the P and the n side. Now, this is all when we have P n junction in equilibrium. So, what happens when I bias my junction. So, the 1st think a going to look at is forward biasing, the P n junction in the case of forward bias. This is my schematic P and n and going to connect the P to the positive side and n to the negative.

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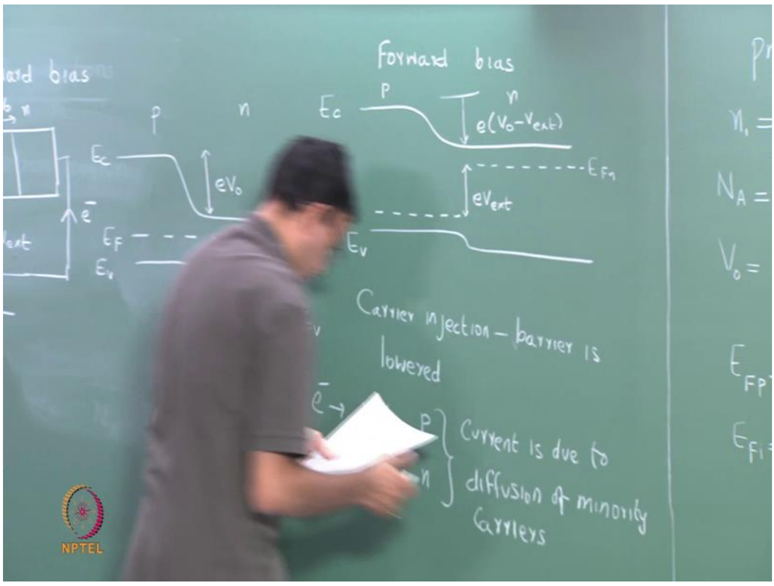

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So, let this v be external there is a contact potential at the junction that is your v naught. So, if you look forward bias you connecting P to the positive end to the negative, which means you are injecting electrons on to the electrons on to the n side, on you are injecting holes on to the P side. Another way if you look at it, you have it an external potential v, that opposes the contact potential v naught.

So, this is something if seen earlier in the case of shot key junction in forward bias, where we saw that the external potential will oppose the potential between the metal and the semiconductor. So, in the case of forward bias, because this opposes the contact potential, the barrier is lowered, and we can show this again in the energy ban diagram. So, let me draw the energy ban diagram 1st in equilibrium.

So, in equilibrium firmly levels line up. So, this is in equilibrium where the barrier is nothing but E v naught. And now apply an external potential that opposes v naught. So, the equivalent saying this is that this barrier is lowered. So, what we can say it that the n side has shifted up and it is shifted up depending upon the value of the external potential. So, if a re draw this forward bias.

This is my P side, now my n side the firmly level has shifted up. So, that the firmly levels no longer line up E f P E f n this shift nothing but E times v external. And the barrier is E times v naught minus v external. So, let me just mark conduction band and the valence band. So, because you are barrier as reduced you now have an injection of careers. So, you have electrons injecting from n to the P a holes from the P to the n. So, we have carrier injunction because barrier is lowered. So, this carrier injunction if look at it we have electrons going from n to P holes going P to n. So, these constitute the current in P n junction in the forward bias an electrons are the minority carrier in the P side. Holes are the minority carriers on the n side. So, what this means is that current is due to the diffusion of minority carriers.

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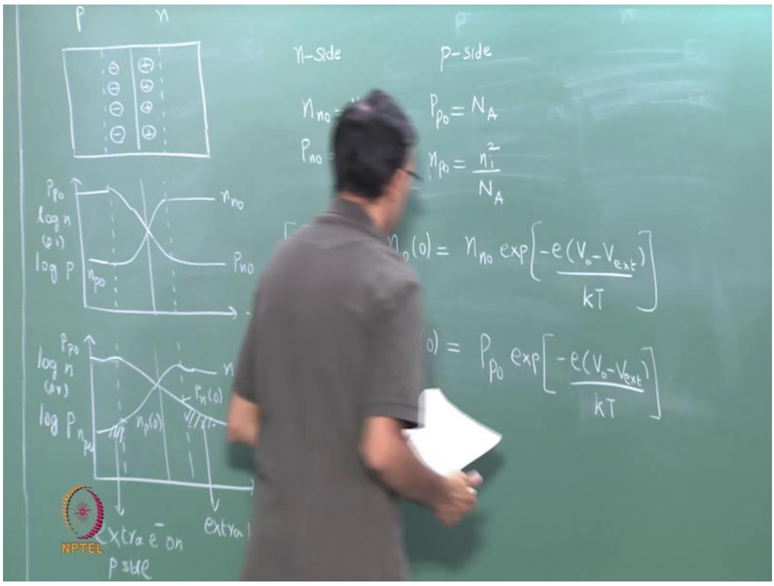

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So, let me now draw the concentration of the electrons and holes across the P n junction in equilibrium and what happens in apply a forward bias. So, once again I will go back to my picture of the P n junction just us schematic. This is the interface between P and n, we have a depletion region. So, that this side is all negative, this side is all positive. So, we looked at how the concentration of electrons and holes changes as a function of distance we looked at is last class when we have P n junction in equilibrium.

So, this is log of n or log of P versus distance. So, let me mark my interface and also depletion region. So, if I plotted log of n this value is nothing but n naught, which is equal to n d and then as you across the value of n drops. Then we had n on the P side. So, n P naught. Similarly, we can plot the concentration of holes, starts of high, which is p, P naught and then goes down P and n naught.

In last class we saw that n, n naught was n d P and naught is nothing but n i square over n d, P naught just a P side n a and n P naught is n i square over n a. So, this is my n side that is my P side. So, this is in the case of equilibrium. So, now we apply forward bias. So, when we apply of forward bias, we are injecting electrons into the n side an injecting holes on to the P side. So, if I once again plot my concentration, this is log of n on log of P and again mark the boundaries. So, injecting some carriers which means as an extra construction of electrons on the P side and ultimately it goes back to you are base line.

So, this we just draw straight is n, n naught. This is n P naught, we have some extra concentration of electrons on the P side. Same way we have some extra holes were being from the P side. So, once again if you draw this that you have P p naught, P n naught and you have some extra holes. So, extra electrons and holes are what there are responsible for the current. So, we have these extra electrons and holes because you reduces the barriers for the electrons and holes move across.

So, if I call the concentration of an electrons at the junction as n P of 0. So, np of 0 is the extra electrons injected on to the P side. Similarly, you have P n of 1, you can write an expression for that exponential minus E v naught minus v external over k t. Similarly, P n naught nothing but P naught exponential minus E v naught minus external over k t. So, these 2 terms represent the access electrons and the access holes there are injected in t of the P n junction because of the forward bias.

So, these are the excess electrons and these are the excess holes. The value is directly proportional to your v external. So, higher the external potential, lower the barrier and then the higher the number of electrons and holes. So, these E electrons and holes are still minority carriers in the case of P n junction, which means they can defuse for some distance, but altimetry they will combine with the majority carriers and get destroyed. So, we can define a diffusion length and the diffusion co efficient for these electrons in holes. So, the diffusion length for the extra electrons in holes we are going to call them L h or L e. This is call the minority carriers diffusion length.

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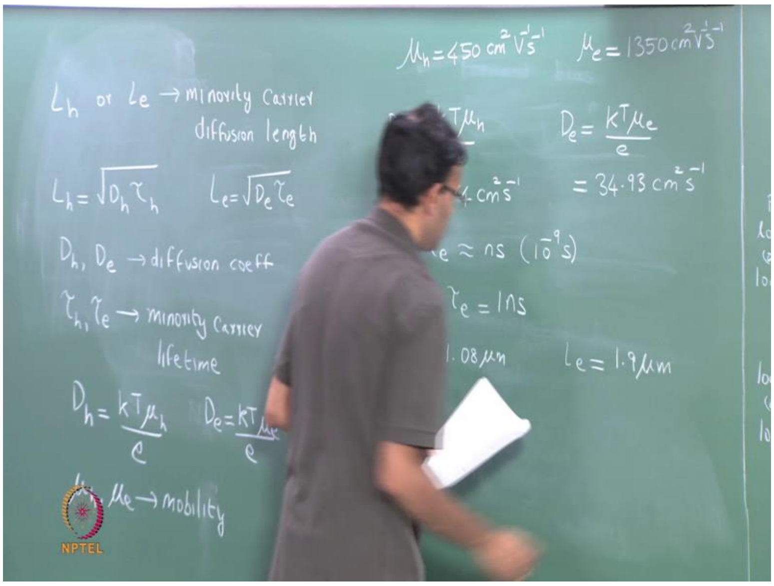

We can relate L to a diffusion co efficient. So, that L h is nothing but t h time tau h square root L e similarly D e tau e. So, D h and D e are diffusion co efficient and t h on tau h and tau e are the minority carrier life time. So, these define the time the electrons in holes can travel in the material before they get re combine and destroyed. So, D h and D e are related to the mobility's. So, that D h k t is new h over E D e is k t new e over e where we are seen earlier that mu h and mu e are the mobility's.

So, let me just put down some numbers in the case of intrinsic silicon. We had mu h to be 450 centimeter square holes per second and we had mu e to be 1350. So, then we can calculate the values for the diffusion co efficient. So, that D h is k t new h of for e. So, we can substitute the numbers a gives your diffusion co efficient of for on 11.64 centimeter square per second. We can do the same thing for the electron k t mu e over e which is nothing but 3493.

So, the diffusion co efficient for the electron is higher, simply because the mobility is higher the tau h and tau e, I said these were the minority carrier re combination times, typically tau h and tau e are of we order of nano seconds, 10 power minus 9 seconds. So, these numbers are different from the scattering times, that we sow earlier is scattering times refers to the time between 2 scattering events.

These times refer to time he take for the electron and hole to re combine. So, these electrons can under multiple scattering, because we saw the scattering time is around picoseconds. So the electron in hold can undergo multiple scattering before the re combined. If I take tau h is equal to tau e to be 1 nano second. We can calculate the diffusion length L h, L is nothing but square root of d times t. So, you get L h to be around 1.08 micro meters and L e you can do a similarly calculation to be around 1.9 micro meters. So, L h and L e refer to the diffusion length of these extra electron and holes before they ultimately re combine with the majority carriers and get eliminated. So, let us go ahead now calculate the current in a P n junction in a case of forward bias. So, I am going to re draw plot of the change in concentration versus distance.

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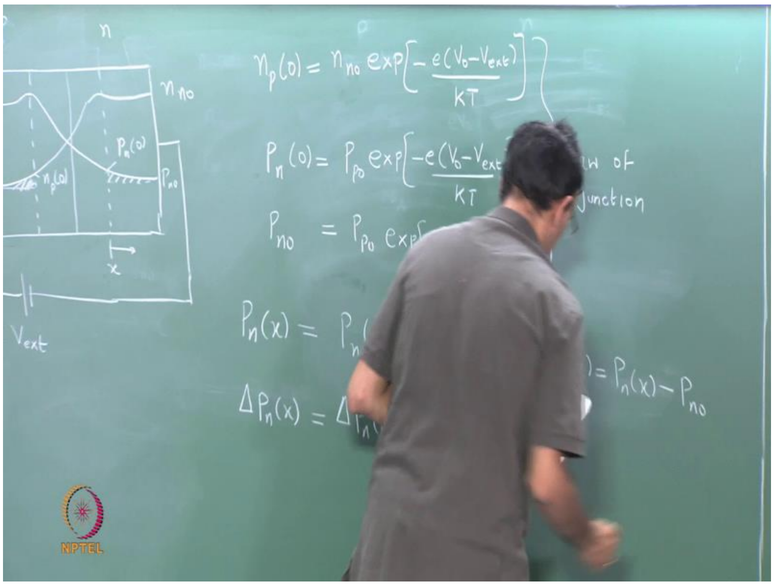

Here is my P n junction, this is my interface. These are the depletion regions is p, that is n. We have P n junction in forward bias. So, P is connected to a positive and n is connected to negative, we saw in this case that we can plot the concentration of holes. So, that there is from excess holes and do the same with electrons. So, you have some excess electrons. So, we can mark the different regions is n naught is P n naught, P naught and the extra carriers some be P n of 1 is P n P see.

So far the sake of the derivation and going to take my origin on the n side at the interface between the depletion region and bulk of the n side. So, I am going to fix that as the origin, n P naught choose your excess electrons naught exponential minus e t P n naught exponential minus E v naught minus v external over k t. We saw this before another way of writing this is nothing but P n naught P p naught exponential. So, this is in the case of equilibrium and this is when we have forward bias. These E equation is together are call law of junction. So, they describe how the junction behaves when you in apply of bias. So, we saw that we have these excess carriers and as you move away from the depletion regions the excess carriers start to re combine and they ultimately are un highlighted.

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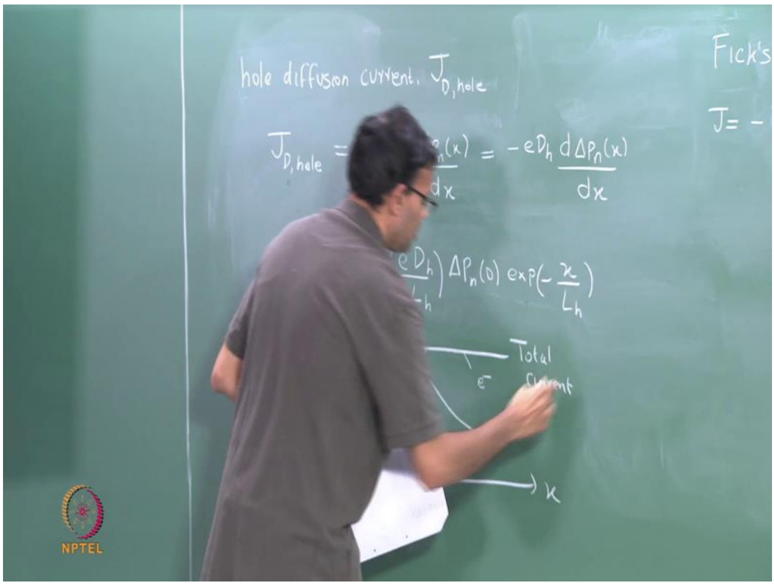

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So, we can calculate or we can write down the expression for the excess holes on the n side as a function of distance x, x is measured from the boundary between the depletion region and the bulks of the n side. So, this access is related to the diffusion length. So, it is P n naught or P n 0 times exponential minus x over L h. So, L h refers to the diffusion length an x refers to the distance from the origin. You can also write an expression for the access carriers. So, delta P and of x should be nothing but delta P n of o times exponential minus x over L h this delta is nothing but delta P of x is P n x minus P n naught.

So, these refers to your extra holes on the n side as a function of distance. We can convert this to a hole current. So, we can write hole diffusion current going to call you J and the whole diffusion current is minus e, the diffusion co efficient of the holes and d P n over d x. This is also the same as writing minus e D h d delta P of n as a function of x over d x. So, this diffusion equation is very similar to your Fick's 1st law. So, Fick's 1st law says that the flack's is minus a diffusion co efficient, divided by your concentration gradient.

So, now, your Flack's is nothing but the hole diffusion current which is equal to minus of a diffusion co efficient and d P over d x or d delta d P or d x is nothing but concentration gradient. So, we can substitute the expression for P n, that we got and do the differential. So, that J d hole is nothing but e D h L h, I will only write the final expression delta P and naught exponential minus x over L h. We can write a similar expression for the current due to the electrons. So, the current due to the holes is a function of a distance. We current due to the electrons we also be a function of distance, but the total current the some of these two, will be a constant. So, if I were to a plot that is my distance x that is the total current.

Let me just mark my 2 depletions regions W p W n in the case of holes. So, you have a majority current due to holes. So, let me just re draw that, in the case of holes, you have a majority current on the P side and start to reduce as we reach the depletion region. And then it becomes minority carrier on the n side. Same way for electrons we have electrons are majority carriers.

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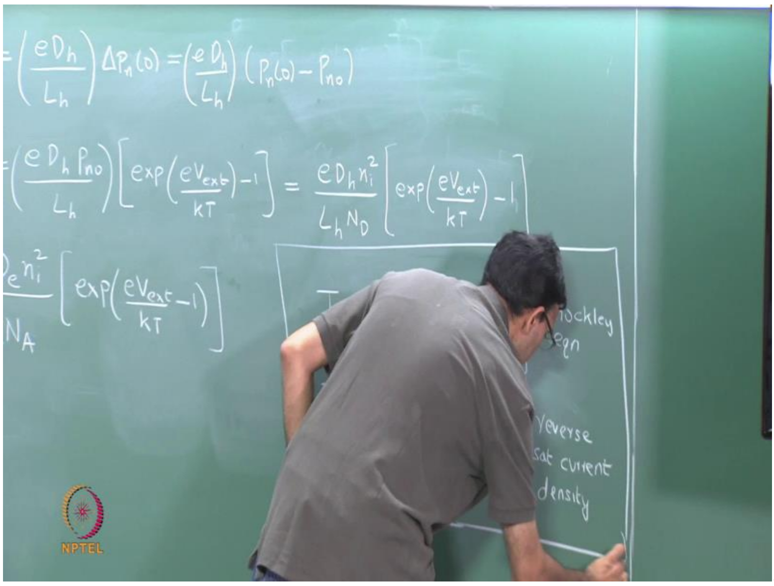

On the n side, then it is start to drop and then finally, it becomes a minority carrier on the P side. So, these are your holes these are the electrons, but if you add both of them to get the total current the total current is a constitute. So, we can evaluate the value of the current at x is equal to 0. So, that we can have a simpler expression. So, let me do that next. So, we can write down the value of the hole current at x is equal to 0 nothing but e D h over L h delta P n of 1.

We saw that this is nothing but e D h over L h P n of 0 minus P n naught. We can substitute the values of the P n of 0 is P n naught and we take out the common terms. We left with e D h P n naught over L h times exponential e v, external over k t minus 1, P n naught is nothing but n i square over n d. This expression becomes e D h n i square L h n d exponential e v external over k t minus 1. We can write a similar expression for the current due to the electrons and it said the total current should be the constant. So, if he add these two, let me just write the current due to the electrons. So, will be e instead of D h you have D e n i square.

Instead of L h you have L e instead of n e you will have n a. So, remember again the electrons are moving on the P side and the holes are the moving on the n side. The rest of the expression is to same external over k t minus 1. So, if we take these 2 and add them, we get an expression for the total current. So, total current J is constant J s naught and exponential. I am going to drop the subtract the external and just write it at as e v k t minus 1.

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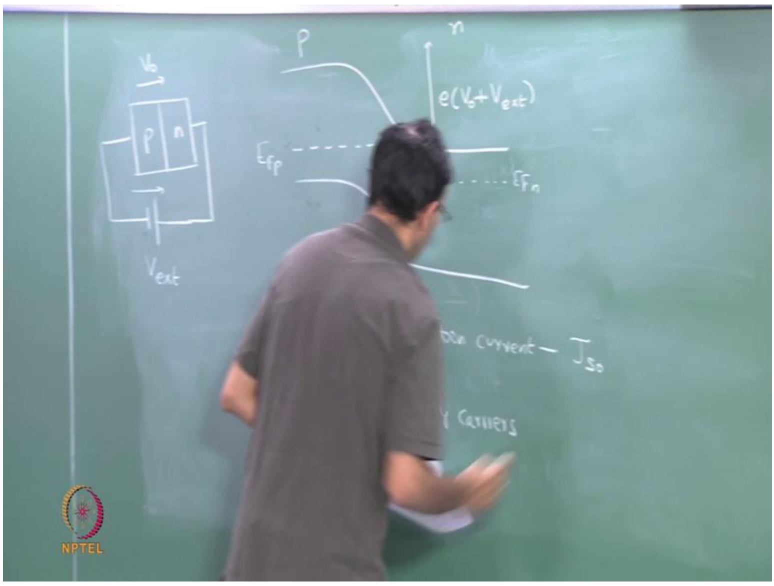

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Well, J s naught is n i square e D h over L h n d plus D e over L e n a. So, this equation is call the shockly equation and this constant term J s naught is called the reverse saturation current density. So, this represents the total current in a P n junction. In the case of a forward bias, the current is because diffusion of the minority carriers. So, electrons on the P side holes on the n side, the current depends upon the external potential. So, higher the value of v higher the current. So, what happens if he now apply a reverse bias to the P n junction.

So, if he apply a reverse bias, we connect the P to the negative and n to the positive. This is your v external, v external now is in the same direction of v naught, which your contact potential. So, just like we did for a shot key junction, it will find that the barrier as gone up. Q a to drown the ban diagram for this this is e f P this is e f n. So, that now the total potential is the P side and is the n side e v naught plus v external. So, in the case of a reverse bias, there is small reverse saturation current and the reverse saturation current happens because we have minority carriers. There are holes and the n side get attract to the negative charge on the P side and then diffuse.

Similarly electrons on the P side will diffuse on to the n side. So, these is small current there is due to the diffusion minority carriers, and the value of the reverse saturation current is nothing but the J s o this is the reverse saturation current just we just direct.

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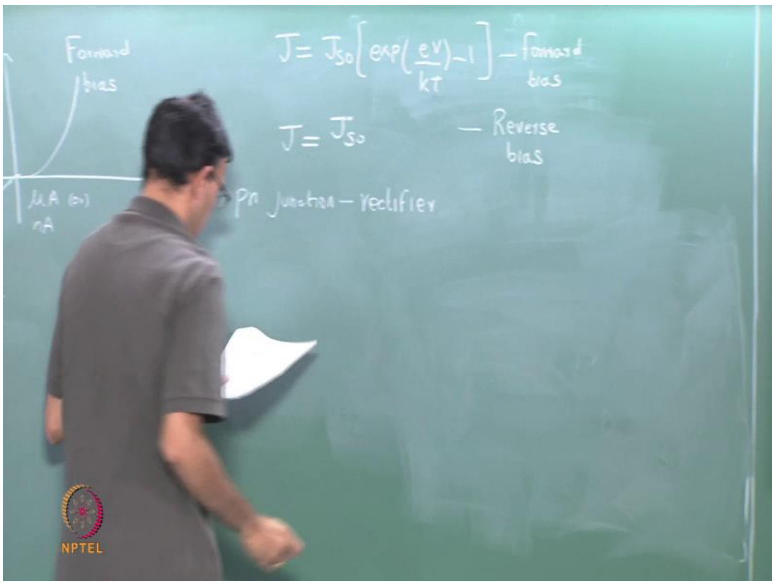

So, let me put to these e together to draw the, i v characteristics for a P n junction. So, let me draw i v characteristics, the 1st quadrant is your forward bias and the 4th quadrant is the reverse bias just extend these access. So, we found out that in the case of a forward bias we have a current that increases exponentially with the applied voltage. So, if you way to draw this, have a current that increase exponentially. Typical values of the current or of the order of milliamps. So, this is the case of forward bias.

In the case of reverse bias, we found that we have a small reverse saturation current, reduced to the diffusion of the minority carriers. So, that J is just J s naught this is reverse bias. If you were to draw this you just draw a small reverse saturation current. The forward bias current is of a of the order of milliamps. The reverse bias current is either micro amps or nano amps, it is must smaller than the forward bias. So, based on this you can say that a P n junction is just a rectifier. So, that it will conduct in one way, that is will conduct during forward bias and during reverse bias it will still conduct, but the current so small that we can says to the resistance is really large.

So, it is equal into say it will naught conduct. Similarly, when we look at a short key junction we found that the short key junction is also a rectifier, it will conduct in the forward direction, but naught in the reverse. The difference between a P n junction and the short key junction is that, the reverse saturation current for a P n junction is much smaller. So, later we will also look at some examples where we compare a shot key junction and a P n junction.

So, today we have looked at a P n junction in bias. So, we found that a P n junction is essentially rectifier. So, it conducts in one way in naught the other. So, for we only looked at junctions which are between the same material. So, P n and n are the same material. Next class we will 1st do an example to get some idea of some of the numbers that are involved and later we look at what happens if we have a junction between different materials.