Fundamentals of electronic materials, devices and fabrication
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Lecture – 11
pn junctions under bias

Let us start with the brief review of the last class. Last class, we started looking at p-n junctions.

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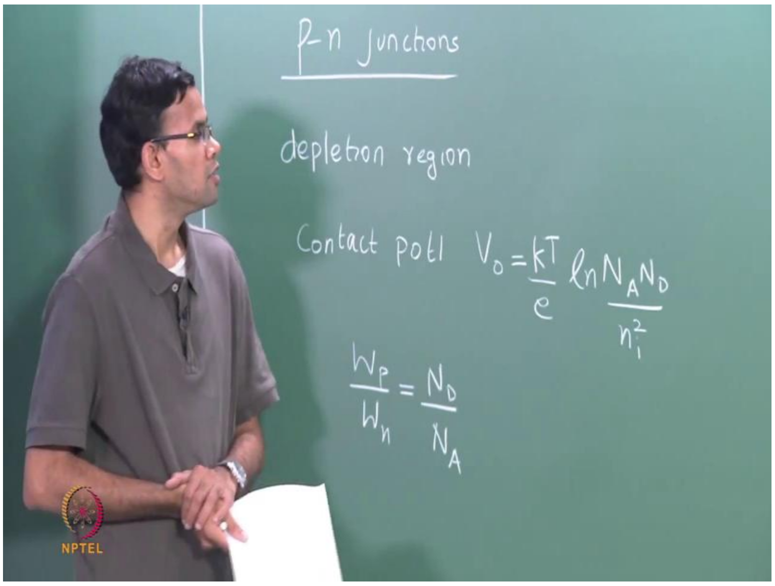

A p-n junction is formed by combining a p-type semiconductor and an n-type semiconductor. So, we said that these junctions are ideal, so that there are no defects. And, both the p and the n-type are from the same material. So, you could have a junction between p-type silicon and n-type silicon. When we form a p-n 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 recombine. So, that we have a depletion region. We also found that because these electrons and holes recombine, they leave behind positively charged donors on the n-side, negatively charged acceptors on the p-side, so that there is an electric field and a contact potential between the junctions. So, we also calculated this value of the contact potential from last class; V_o where N_A and N_D are the concentrations 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 dopants, so that $\frac{W_p}{W_n} = \frac{N_D}{N_A}$.

So, today we are going to continue to look further on p-n junctions, but we are going to consider cases when we bias the junction. So, we will look at both forward bias and a reverse bias. Before we do that, I want to link the p-n junction to the energy band diagram in the case of a semiconductor. So, let me go back to the example that we looked at last class.

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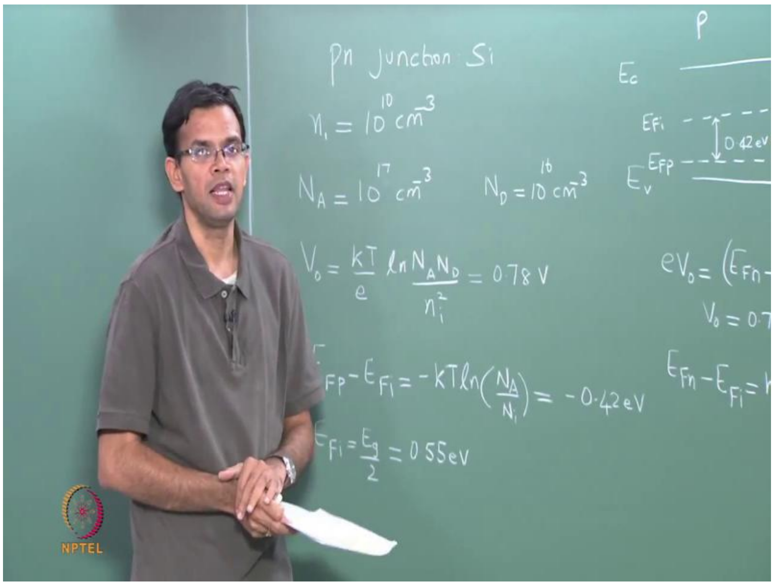

So, we had a p-n junction with the material being silicon. So, n_i for silicon is 10^{10} cm^{-3}. We said that we had a p-side with an acceptor concentration of 10^{17}. And, we have an n-side with the donor concentration of 10^{16}.

So, last class we calculated the contact potential in this case. And, when we substitute the values we get V_o to be 0.78 volts. So, what I want to do is to link the contact potential to the location of the Fermi levels in the p and the n-side. So, let us consider the p-side separately and the n-side separately. So, let me draw them here. So, this is my p-type, it is my n-type; they are both silicon. So, the band gap is the same. So, what I want to do is to put the Fermi level on the p and the n-side. To calculate the position of the Fermi level, we go back to the formula that we used in the case of extrinsic semiconductors. So, $\frac{E_{Fp}-E_{Fi}}{kT}\ln\frac{N_A}{N_i}$. So, if you do the numbers, this is equal to -0.42 electron volts.

So, in the case of a p-type the Fermi level is located -0.42 electron volts below the intrinsic Fermi level. So, just for simplicity I will take the intrinsic Fermi level to be exactly at the band gap, in the case of silicon this not entirely true. It will be slightly shifted because the effective masses are not the same. But, for all practical purposes it is very close to the center of the band gap. So, E_{Fi} is 0.55.

So E_{Fp}, we can get by substituting the value of E_{Fi}. So if I mark it here, E_{Fi} is the center. And, E_{Fp} which is the Fermi level on the p- type is 0.42 electron volts below E_{Fi}. We can do the calculation for the n-side. If you do the numbers, $\frac{E_{Fn}-E_{Fi}}{kT}$ ln. Instead of N_A, it will be $\frac{N_D}{N_i}$. Once again, we can substitute in the values. We get this to be 0.36 electron volts above the intrinsic Fermi level.

So, in this case E_{Fn} is 0.36 volts. So, when I bring my p and n-type semiconductor together, I know that the Fermi levels must line up. So, you can either say that the p has shifted up or the n has shifted down. And, this shift is equal to the distance between the 2 Fermi energies. So, this overall distance is nothing but my contact potential eV_o. And, if you look at it eV_o, this E_{Fi}, sorry, $E_{Fn} - E_{Fi} + E_{Fp} - E_{Fi}$ so that this entire distance, which is equal to 0.78 electron volts, which gives you V_o to be 0.78 volts; which is the same value that we calculate from the formula.

So, the contact potential is nothing but the difference between the Fermi levels on the p and the n-side. Now, this is all when we have a p-n junction in equilibrium. So, what happens when I bias my junction?

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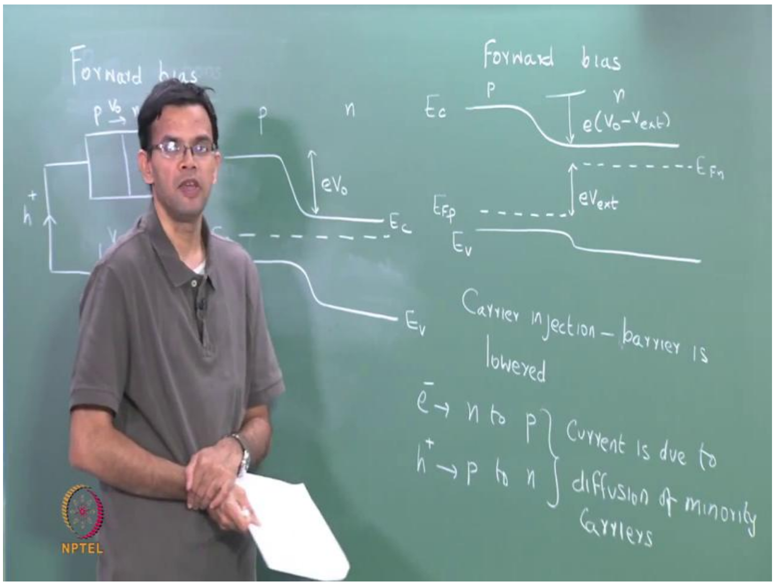

So, the first thing we are going to look at is forward biasing the p-n junction. In the case of forward bias, this is my schematic p and n. I am going to connect the p to the positive side and n to the negative. So, let this be V_{ext}. There is a contact potential at the junction that is your V_o. So, if you look at forward bias you are connecting p to the positive, n to the negative, which means you are injecting electrons on to the n-side on your injecting holes on to the p-side.

And, on the other way, if you look at it you have an external potential V that opposes the contact potential V_o. So, this is something you have seen earlier in the case of a short key junction in forward bias, where we saw that the external potential will oppose the potential between the metal and the semi conductor. 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 band diagram.

So, let me draw the energy band diagram. First, in equilibrium, so in equilibrium the Fermi levels line up. So, this is in equilibrium where the barrier is nothing but eV_o. I now apply an external potential that opposes V_o. So, the equivalent of saying this is that this barrier is lowered. So, what we can say is that the n-side has shifted up. And, it is shifted up depending upon the value of the external potential.

So, if I redraw this in forward bias, this is my p-side. Now, my n-side, the Fermi level has shifted up, so that the Fermi levels no longer line up E_{Fp} E_{Fn}. This shift is nothing but e x V_{ext}. And, the barrier is e x V_o - V_{ext}. So, let me just mark the conduction band and the valence band.

So because your barrier is reduced, you now have an injection of carriers. So, you have electrons injecting from the n to the p and holes from the p to the n. So, we have carrier injection because the barrier is lowered. So, this carrier injection if you look at it, you have electrons going from n to p; holes going from p to n. So, these constitute the current in a p-n junction in the forward bias. And, electrons are the minority carriers in the p-side; holes are the minority carries on the n-side. So, what this means is that current is due to the diffusion of minority carriers. So, let me now draw the concentration of the electrons and holes across the p-n junction in equilibrium and what happens when we apply a forward bias.

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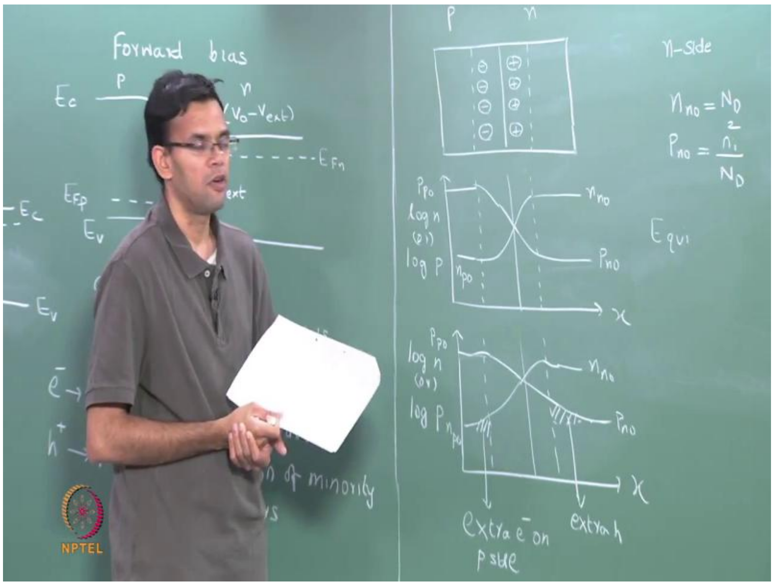

So, once again I will go back to my picture of the p-n junction, just a schematic. This is the interface between p and n. We have a depletion region, so that this side is all negative and this side is all positive. So, we looked at how the concentration of electrons and holes changes as a function of distance. We looked at this last class, when you have a p-n junction in equilibrium. So, this is log(n) or log(P) versus distance. So, let me mark my interface and also the depletion region.

So if I plotted log(n), this value is nothing but n_{no} which is equal to N_D, and then as you go across, the value of n drops. Then we had n on the p-side so, n_{po}. Similarly, we can plot the concentration of holes, starts of high, so which is P_{po} and then goes down P_{no}.

In last class, we saw that n_{no} was N_D; P_{no} is nothing but $\frac{n_i^2}{N_D}$. P_{po} which is the p-side, N_A. And, N_{Po} is $\frac{n_i^2}{N_A}$. So, this is my n-side; that is my p-side. So, this is in the case of equilibrium.

So, now we apply a forward bias. So, when we apply a forward bias we are injecting electrons into the n-side and we are injecting holes on to the p-side. So, if I once again plot my concentration. So, this is log(n) on log(p) and can again mark the boundaries. So, we are injecting some carriers; which means there is an extra concentration of electrons on the p-side and then ultimately it goes back to your base line. So this, we just draw it straight is n_{no} this is n_{po}. We have some extra concentration of electrons on the p-side. Same way, we have some extra holes that are being injected from the p-side. So once again if you draw this, so that you have P_{po} P_{no} and you have some extra holes. So, these extra electrons and holes are what that are responsible for the current. So, we have these extra electrons and holes because you have reduced the barrier for the electrons and holes to move across.

So, if I call the concentration of electrons at the junction as $n_p(0)$. So, $n_p(0)$ is the extra electrons that are injected on to the p-side. Similarly, you have $p_n(0)$. We can write an expression for that.

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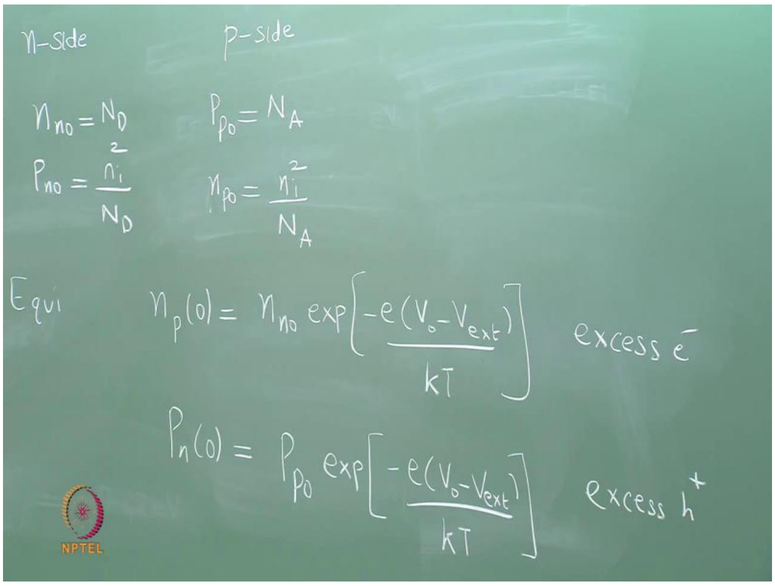

$exp\frac{-e(V_o-V_{ext})}{kT}$ similarly, P_{no} is nothing but $P_n(0) = P_{po}exp\frac{-e(V_o-V_{ext})}{kT}$. So, these 2 terms represent the excess electrons and the excess holes that are injected into your p-n junction because of the forward bias. So, these are the excess electrons and these are the excess holes. The value is directly proportional to your V_{ext}. So, higher the external potential lower the barrier and then higher the number of electrons and holes.

So, the electrons and holes are still minority carriers in the case of p-n junction, which means they can diffuse for some distance. But, ultimately they will combine with the majority carriers and get destroyed. So, we can define a diffusion length and the diffusion coefficient for these electrons and holes. So, the diffusion length for the extra electrons and holes, we are going to call then L_h or L_e. This is called the minority carrier diffusion length.

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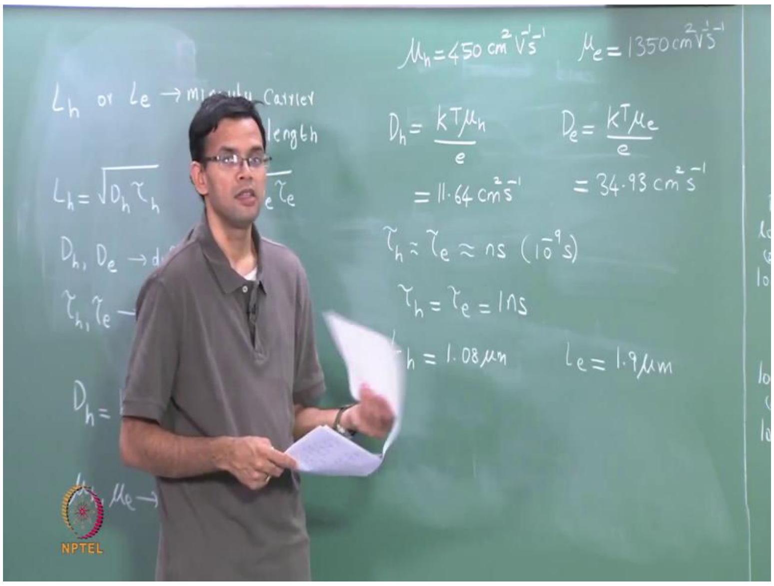

We can relate L to a diffusion coefficient, so that L_h is nothing but $D_h\ \tau_h \sqrt{L_e}$, similarly $D_e\ \tau_e$. So, D_h and D_e are diffusion coefficients and T_h or τ_h and τ_e are the minority carrier lifetime. So, these define the time the electrons and holes can travel in the material before they get recombined and destroyed.

So, D_h and D_e are related to the mobilities, so that D_h is $\frac{kT\mu_h}{e}$, D_e is $\frac{kT\mu_e}{e}$; where we have seen earlier that μ_h and μ_h are the mobility. So, let me just put down some numbers. In the case of intrinsic silicon, we had μ_h to be $450\ cm^2\ V^{-1}\ s^{-1}$ and we had μ_e to be 1350. So, then we can calculate the values for the diffusion coefficient, so that D_h is $\frac{kT\mu_h}{e}$. So, we can substitute the numbers that gives you a diffusion coefficient of around $11.64\ cm^2\ s^{-1}$. We can do the same thing for the electron; $\frac{kT\mu_e}{e}$, which is nothing but $34.93\ cm^2\ s^{-1}$. So, the diffusion coefficient for the electron is higher, simply because the mobility is higher.

So τ_h and τ_e, I said these were the minority carrier recombination times. Typically, τ_h and τ_e are of the order of nanoseconds is 10^{-9} second. So, these numbers are different from the scattering times that we saw earlier so, scattering times refers to the time between 2 scattering events. These times refer to the time it takes for the electron and hole to recombine. So, these electrons can undergo multiple scatterings because we saw that a scattering time is around picoseconds. So, the electron and hole can undergo multiple scattering before they recombine. If I take $\tau_h = \tau_e$ to be one nanosecond. We can calculate the diffusion length L_h. L is nothing but $\sqrt{D\,x\,t}$. So, you get L_h to be around 1.08 micrometers and L_e, can do a similar calculation to be around 1.9 micrometers. So, L_h and L_e refer to the diffusion length of these extra electrons and holes before they ultimately recombine with the majority carriers and get eliminated.

So, let us go ahead and now calculate the current in a p-n junction in the case of forward bias. So, I am going to redraw the plot of the change in concentration versus distance.

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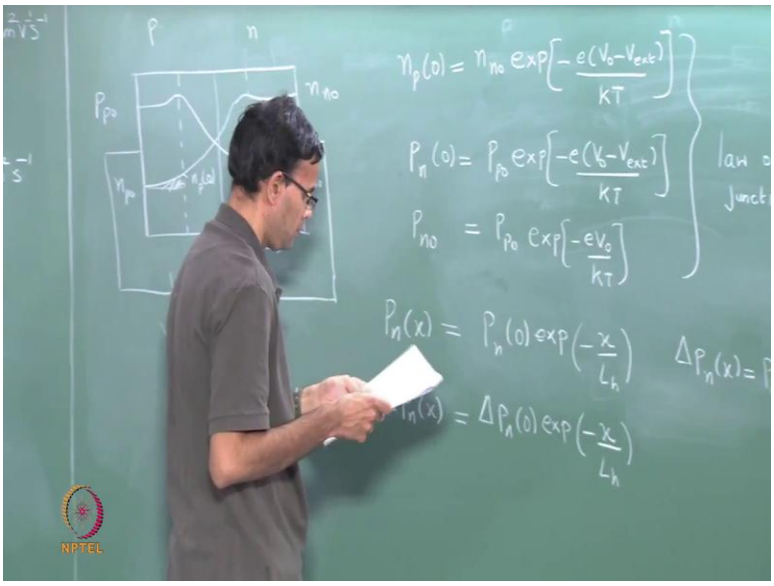

So, here is my p-n junction. This is my interface, these are the depletion regions, this is p and that is n. We have a p-n junction in forward bias, so p is connected to the positive and n is connected to the negative. We saw in this case that we can plot the concentration of holes, so that there is some excess holes can do the same with electrons. So, you have some excess electrons.

So, we can mark the different regions. This is n_{no} this is Pno, P_{po}, P_{no}. And, the extra carriers; this will be $p_n(0)$ so, this will be $n_p(0)$. So, for the sake of derivation I am going to take my origin on the n-side at the interface between the depletion region and the bulk of the n-side. So, I am going to fix that as the origin n_{p0}, which is your excess electrons $n_{no}\ exp\frac{-e(V_o-V_{ext})}{kT}$. $P_{no} = P_{po}\ exp\frac{-e(V_o-V_{ext})}{kT}$. We saw this before.

Another way of writing this is nothing but P_{no} is P_{po} exponential. So, this is in the case of equilibrium and this is when we have a forward bias. These equations together are called law of junction. So, they describe how the junction behaves when you apply a bias. So, we saw that we have these excess carriers and as you move away from the depletion region, the excess carriers start to recombine and they ultimately are unhighlighted. 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 bulk of the n-side. So, this x is related to the diffusion length. So, it is P_{no} or $P_{no} exp \frac{x}{L_h}$. So, L_h refers to the diffusion length and x refers to the distance from the origin.

You can also write an expression for the excess carriers. So delta $\Delta P_n(x)$, which will be nothing but $\Delta P_n(0) exp \frac{-x}{L_h}$. This Δ is nothing but $\Delta P_n(x)$ is $P_n(x) - P_{no}$. So, these refers to your extra holes on the n-side as the function of distance. We can convert this to a hole current.

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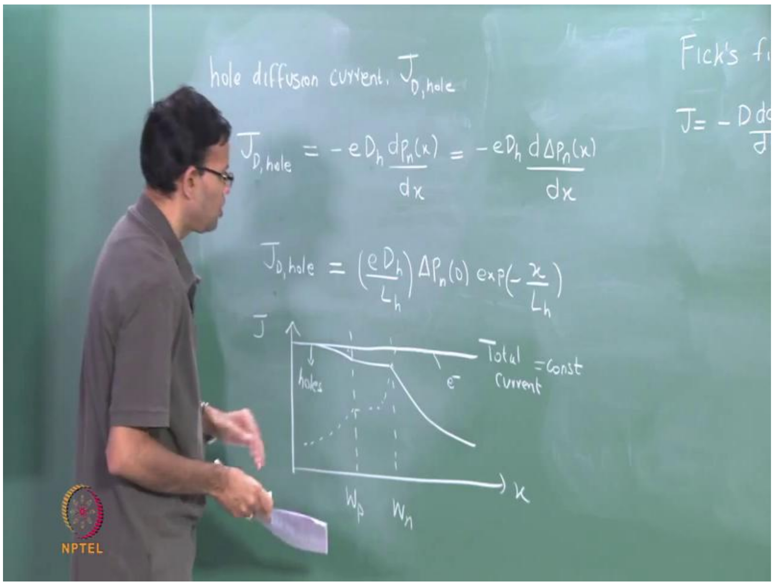

So, we can write a hole diffusion current; going to call it J. And, the hole diffusion current is -e the diffusion coefficient of the holes times $\frac{dp_n(x)}{dx}$. So, this is also the same as writing; $\frac{-eD_h d\Delta P_n(x)}{dx}$. So, this diffusion equation is very similar to your Fick's first law.

So, Fick's first law says that the flux is -(diffusion coefficient) divided by your concentration gradient. So, now your flux is nothing but the hole diffusion current, which is equal to minus of a diffusion coefficient. And, $\frac{dp}{dx}$ or $\frac{d\Delta p}{dx}$ is nothing but a 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 $P_{no}\ exp\frac{-x}{L_h}$.

We can write a similar expression for the current due to the electrons. So, the current due to the holes is a function of distance. The current due to the electrons will also be a function of distance. But, the total current with the sum of these 2 will be a constant. So, if I were to plot that this makes distance x; that is the total current. Let me just mark my 2 depletion regions where W_p W_n, in the case of holes. So, you have a majority current due to holes.

So, let me just redraw 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 a minority carrier on the n-side, same way for electrons. You have electrons are the majority carriers on the n-side, then it starts 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 constant. So, we can evaluate the value of the current at x equal to 0, so that we can have a simpler expression. So, let me do that next.

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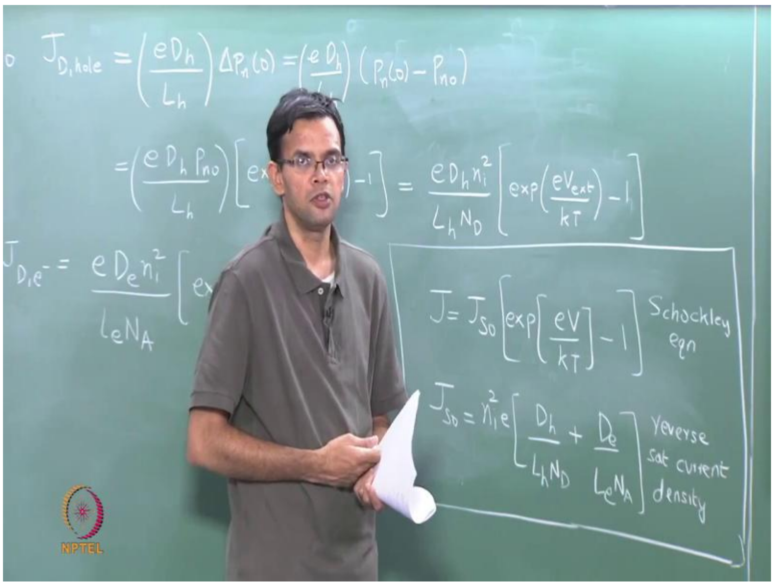

So, I can write down the value of the hole current at x equal to 0, nothing but $\left(\frac{-eD_h}{L_h}\right) P_n(0)$. We saw that this is nothing but $\left(\frac{eD_h}{L_h}\right) P_n(0)\text{-}\ P_{n0}$. We can substitute the values for $P_n(0)$ and P_{no}. And, we take out the common terms. You are left with $\left(\frac{eD_hP_{no}}{L_h}\right)\left[exp\left(\frac{eV_{ext}}{kT}\right) - 1\right]$; P_{no} naught is nothing but $\frac{n_i^2}{N_D}$. This expression becomes $\left(\frac{eD_hn_i^2}{L_hN_D}\right)\left[exp\left(\frac{eV_{ext}}{kT}\right) - 1\right]$. We can write a similar expression for the current due to the electrons. And, we said that the total current should be a constant. So if we add these 2, let me just write the current due to the electrons. So, it will be e. Instead of D_h, you have D_e n_i^2; instead of L_h, you will have L_e and instead of n_e, you will have N_A. So, remember again the electrons are moving on the p-side and the holes are moving on the n-side, but the rest of the expression is the same external over k T - 1. So, if we take these 2 and add them we get an expression for the total current. So, total current J constant J_{so} x exp, I am going to drop the subscript V_{ext} and just write it as eV, kT - 1, where J_{so} is $n_i^2 e\left[\frac{D_h}{L_hN_D} + \frac{D_e}{L_eN_A}\right]$. So, this equation is called the Shockley equation. And, this constant term J_{so} 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 of 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.

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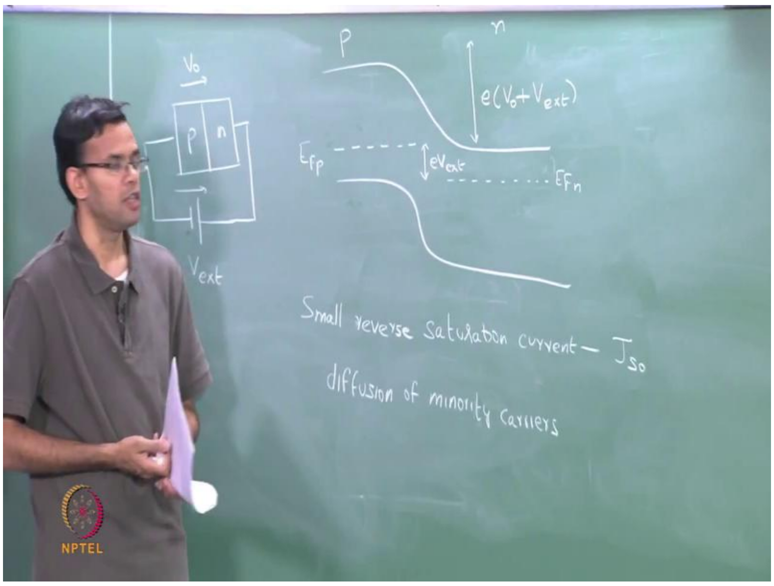

So, what happens if we now apply a reverse bias to the p-n junction? So if we apply a reverse bias, we connect the p to the negative and n to the positive. So, this is your V external. V external now is in the same direction of V_o naught which is your contact potential. So just like we did for a schottky junction, we will find that the barrier has gone up. If you were to draw the band diagram for this, this is E_{Fp} and this is E_{Fn}. So that, now the total potential, this is the p-side and this is the n-side, this is $eV_o + V_{ext}$. So, in the case of a reverse bias there is a small reverse saturation current. And, the reverse saturation current happens because we have minority carriers that are holes on the n-side get attracted 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, there is a small current that is due to the diffusion of minority carriers. And, the value of the reverse saturation current is nothing but the J_{so}. So, this is the reverse saturation current that we just derived. So, let me put these 2 together to draw the I-V characteristics for a p-n junction.

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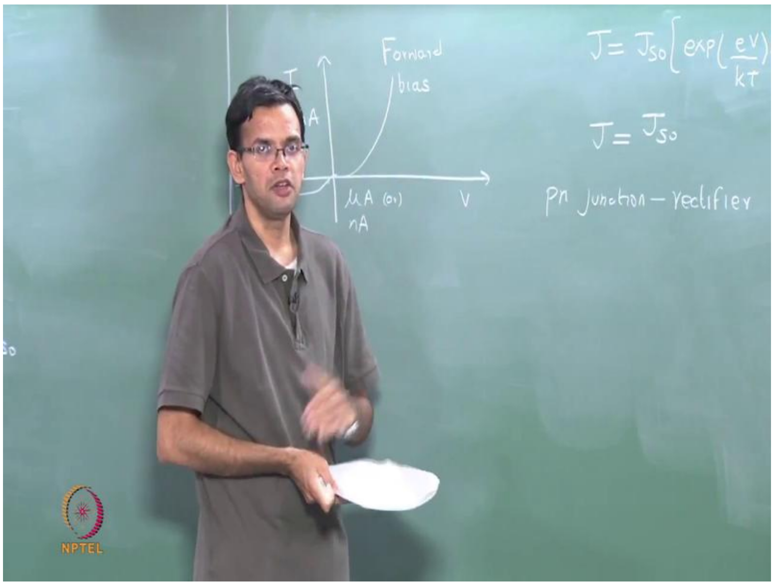

So, let me draw the I-V characteristics. So, the first quadrant is your forward bias and the fourth quadrant is your reverse bias. You just extend this axis. So, we found out that in the case of forward bias we have a current that increases exponentially with the applied voltage. So if you were to draw this, have a current that increases exponentially. Typical values of the current are of the order of milli amps. So, this is in the case of forward bias. In the case of a reverse bias, we found that we have a small reverse saturation current that is due to the diffusion of the minority carriers so that, J is just J_{so} this is in reverse bias.

If you were to draw this, you would just draw a small reverse saturation current. The forward bias current is of the order of milli amps. The reverse bias current is either micro amps or nano amps. It is much smaller than the forward bias. So, based on this we can say that a p-n junction is just a rectifier. So that, it will conduct in one way that is, it will conduct during forward bias. And, during reverse bias it will still conduct, but the current is so small that you can say that the resistance is really large. So, it is equivalent to saying it will not conduct.

Similarly, when we looked at a schottky junction we found that the schottky junction is also a rectifier. It will conduct in the forward direction, but not in the reverse. The difference between a p-n junction and a schottky 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 will compare a schottky junction and a p-n junction.

So, today we have looked at a p-n junction in bias. So, we have found that a p-n junction is essentially a rectifier. So, it conducts in one way and not the other. So far we have only looked at junctions which are between the same material, so p and n are the same material. Next class, we will first do an example to get some idea of some of the numbers that are involved. And, later we will look at what happens if we have a junction between different materials.