Elements of Solar Energy Conversion
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Lecture - 32

Hello everybody. Welcome back to this series of lecture on Elements of Solar Energy Conversion, and we are looking at the photovoltaic conversion mechanisms the basics of it. So, today we are here, at lecture number 32, ok.

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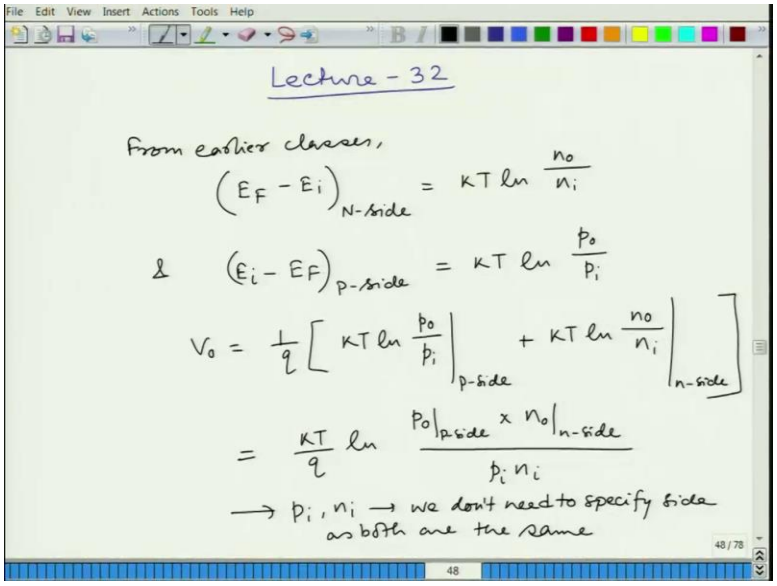

So, for the photovoltaic conversion, what we ended up in the last class with the p-n junction diode ok. So, when we bring one P-type semiconductor and one N-type semiconductor together in close contact then, we have seen the bands will bend as well as it will have a constant Fermi level throughout the junction across the junction ok. And that led us to see what would be the built-in potential and why.

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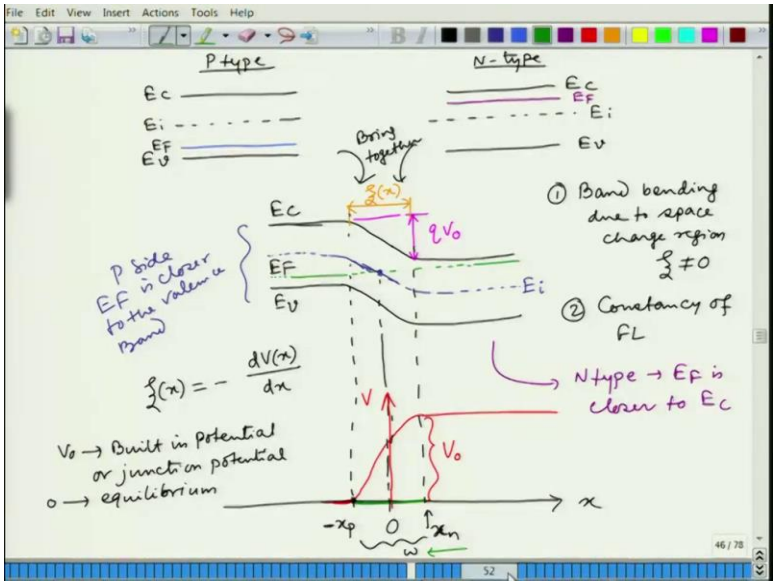

So, this was the picture we have seen in the last class, right, and this built-in potential V_o in the equilibrium potential, which is just obtained because of this close contact of two types of semiconductors ok.

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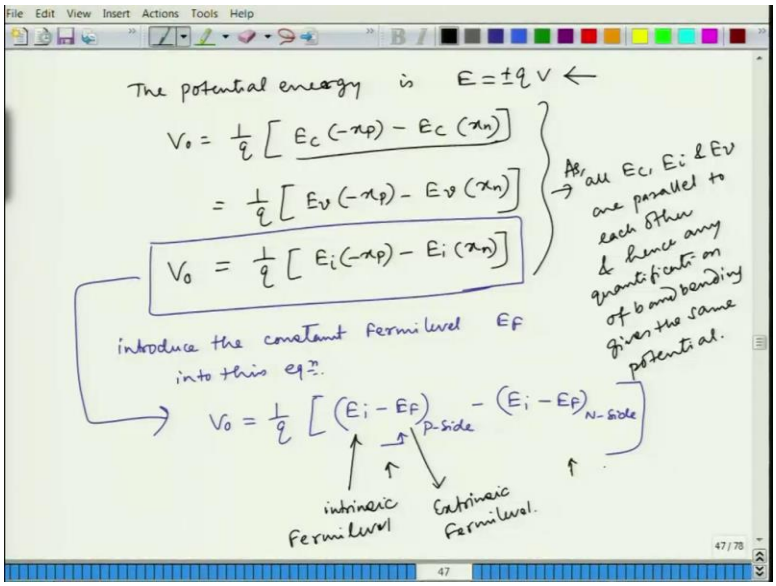

And we have also quantified that quantity which is the built-in potential, and that depends on the distance between the intrinsic and extrinsic Fermi level in the P-type and the same for the N-type ok. So, here this E_i stands for the intrinsic level or intrinsic Fermi level, and this E_F stands for the extrinsic Fermi level. So, we quantified it in terms of for the; the first term here is for the P-side and the second term here is for the N-side ok.

So, let us look at it now with individual doping concentration. So, from earlier classes what we have seen that this shift in Fermi level because of doping can be quantified in this fashion. On the N-side, it will be the $ln\frac{n_o}{n_i}$; n_o is the electron concentration in the equilibrium condition and n_i is the intrinsic electron concentration ok? So, you have seen this in the other

form; that means, n_o we have expressed in terms of n_i into exponential E_F minus E_i divided by KT.

So, just now, we have used the log form of that. And similarly, for the P-type, it is KT $ln \frac{p_o}{p_i}$. Again, this p_o stands for the whole concentration under equilibrium for the extrinsic or doped semiconductor and p_i is the intrinsic doped intrinsic concentration of the holes ok.

So, now, in the expression of built-in potential now we can replace these two quantities the shift in Fermi level with this KT natural log terms and this for the P-side plus KT $ln \frac{n_o}{n_i}$ which is at the N-side, ok. So, now, we can combine them bring KT outside, and we can do that p_o in P-side multiplied by n_o in N-side divided by p_i*n_i.

So, p_i*n_i; we do not have to specify which side it is because it is the same base material. Suppose it is silicon and one side is doped with aluminum, and the other side is doped with phosphorous. So, that is how we are distinguishing the P-side and N-side. So, p_i*n_i here, I should note that p_i and n_i we do not need to specify side as both are the same right. So, intrinsic p_i and n_i, which is the intrinsic value no doping, so both sides have the same value, ok.

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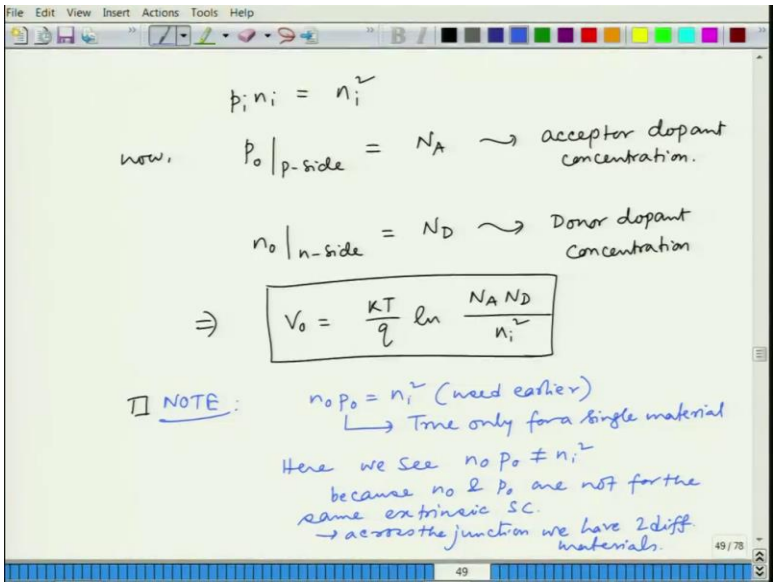

And this p_i n_i; we have seen earlier that it is n_i^2 Because p_i is equal to n_i for intrinsic semiconductor ok, now, if we look closely at the extrinsic value, the p_o in the p-side that is what depends on the concentration or that is equal to the concentration of ionized acceptor donor.

So, this p_o in p-side is nothing, but N_A, which is the acceptor dopant concentration ok. And on the other hand, n naught in n-side is nothing but N_D, which is the donor dopant concentration. On the n-side, you have donor doping, which is N_D. So, now, if we replace these values, we can write

$$V_o = \frac{KT}{q} ln \frac{N_A N_D}{{n_i}^2}$$

Now, we do not have to specify the side because N_A is always in the p-side, and N_D is always in the n-side ok.

And the denominator, you can write just the ${n_i}^2$, because p_i n_i is equal to ${n_i}^2$. So, that is again a very important relationship, ok. Now, one thing I should make a note of it and let me use another color because this causes confusion in a lot of students. So, I should make a specific note of caution that you do not get confused about this thing. So, note that; $n_o p_o = {n_i}^2$we have used it earlier, ok. And this is true only for a single material. So, this is true only for a single material.

So, if you take either a p doped semiconductor or n doped semiconductor; for them, $n_o p_o = {n_i}^2$ that is what we said that you can only increase the concentration of one type of charge carrier at the cost of the other because the product will always be determined by the intrinsic semiconductor concentration or intrinsic carrier concentration squared, ok.

So, here we see $n_o p_o \neq {n_i}^2$ Because the n_o and p_o are not for the same extrinsic semiconductor, right. We have two different materials in n-side and p-side across the junction we have two different materials; across the junction, we have two different materials.

So, do not get confused by only the formula $n_o p_o = {n_i}^2$; that is true only for a single material, and that is why we were insisting upon writing which side we are looking at p_o at in p-side, n_o in n-side.

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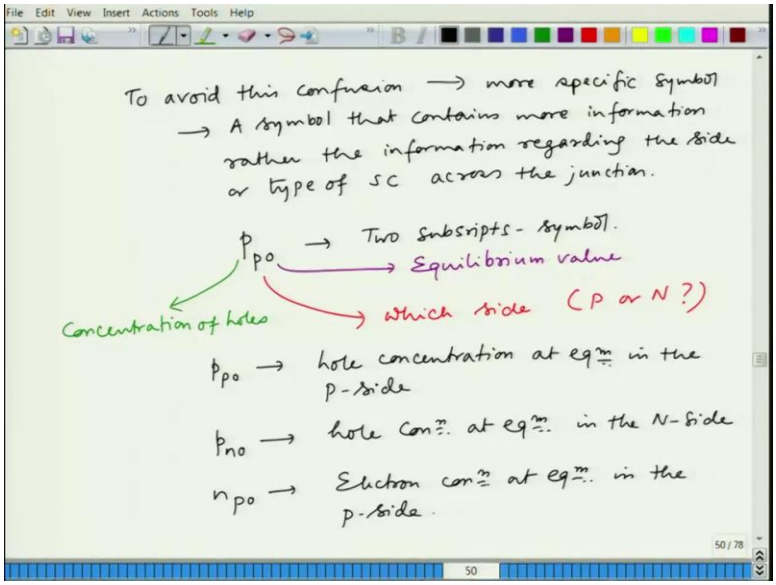

So, to avoid this confusion about what we need, we need a more specific symbol, ok. A symbol that contains more information rather than the information regarding which side we are regarding the side or type of semiconductor in the or across the junction. Is not it? So, let us use that formula.

Let us say that we use the symbol with two subscripts, ok. So, two subscripted or two subscript symbol and what does it mean? It means this p is just the concentration of holes, just like before. And this o is also just like before the equilibrium value ok. And what we introduce now is this information about side, which side; p or n. So, in this case, it is the P-side.

So, this p_o; it means hole concentration at equilibrium in the P-side ok. Similarly, we can write p n naught; that means hole concentration at equilibrium in the N-side. Is not it? And another example is electron concentration at equilibrium in the P-side ok. So, now, we are on the solid ground whether which will not cause any confusion in further analysis.

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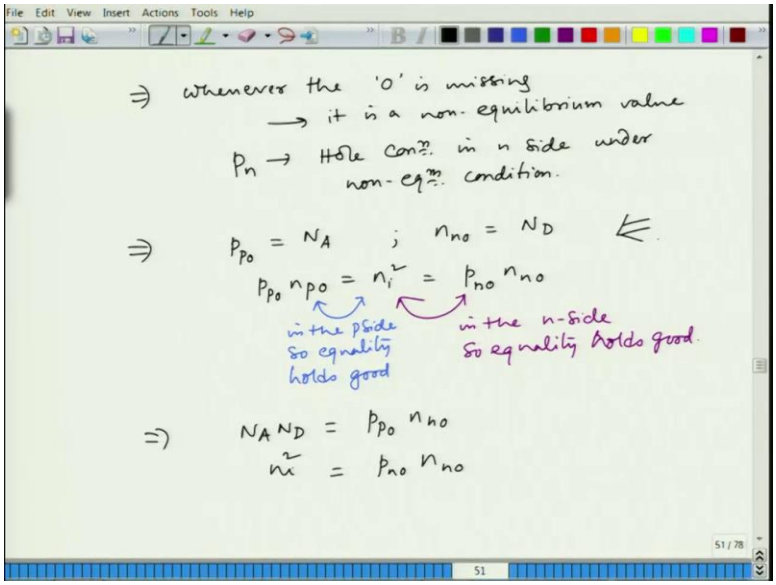

And we should mention that whenever the o is missing, that means it is a non-equilibrium value. So, p_n this will stand for hole-concentration in the n-side under non-equilibrium condition ok. So, enough about the symbols.

So, now, what can we write with this change symbol? So, p_{po} is nothing but our acceptor dopant concentration, and similarly, n_{no} is N_D right dopant donor concentration, and $n_{po}p_{po} = {n_i}^2$. Now, we are talking about a single side. So, that equality with ${n_i}^2$ holds good and similarly, again if we use the same side, then also the equality will hold good ok.

So, because let me just say that this in the p-side. So, equality holds good, and this thing is again on the n-side. So, again equality holds good, hopefully. Now, there is no confusion, and we can write this N_AN_D because we need it for the built-in potential expression.

So, $N_AN_D = n_{no}p_{po}$. And what is coming in the denominator of the natural log was ${n_i}^2$ which is $n_{no}p_{no}$. So, be careful about distinguishing between the normal symbol and the subscript; otherwise, it may be messy.

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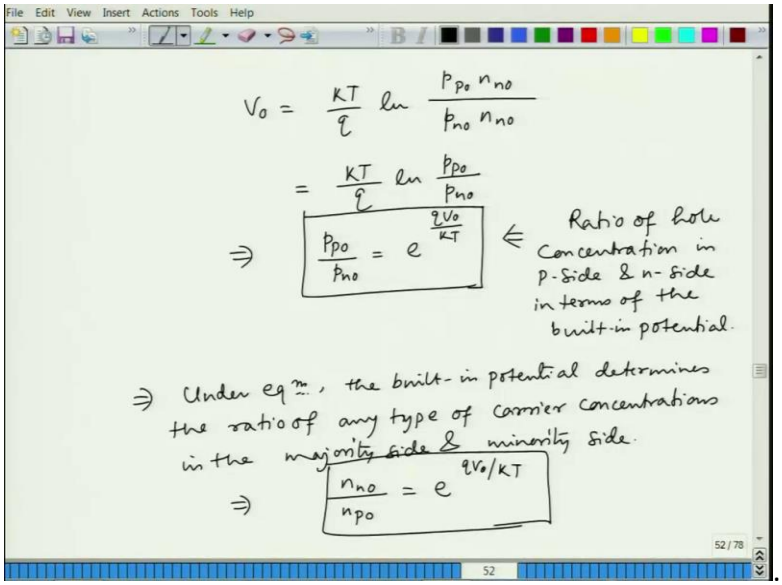

So, with these modified quantities, what we can write

$$V_o = \frac{KT}{q} ln \frac{p_{po} n_{no}}{p_{no} n_{no}}$$

So, now, n_{no} cancels out. So, you have $\frac{KT}{q} ln \frac{p_{po}}{p_{no}}$. So, you can also write

$$\frac{p_{po}}{p_{no}} = e^{\frac{qV_o}{KT}}$$

Now, what we have done is the hole concentration in the p-side and n-side; the ratio we have obtained in terms of the built-in potential ok. So, this is the expression of the ratio of hole-concentration in p-side and n-side in terms of the built-in potential got it. So, we can write that under equilibrium; the built-in potential determines the ratio of any type of carrier concentration in the majority side and minority side.

What do you mean by the majority side? Because the hole is the majority on the p-side and it is the minority on the n-side; so that, the ratio is given in terms of the built-in potential. So, of course, the same equation you can see that you can write for the electron concentration. So, that means

$$\frac{n_{no}}{n_{po}} = e^{\frac{qV_o}{KT}}$$

Now, n is the majority carrier in the n-side, or the electron is the majority carrier in the n-side, and it is the minority on the p-side, ok.

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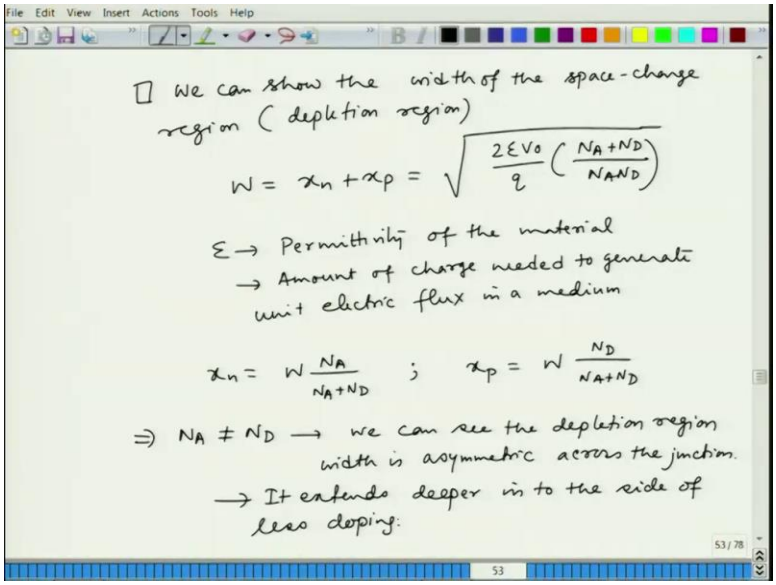

And, one thing I am not showing, but we can show the width of the space charge region, which is also called depletion region because the charge gets depleted within that particular region. So, it is also called the depletion region. So, that can be shown to be $x_n + x_p$, right with this, the width in the space charge region width in the n-side plus the space charge region width in the p-side and that can be shown to be this ok.

So, let me just remind you what I mean by space charge region width. So, here you see, this is the space charge region width, and it is the summation of this x_n here, and x_p here, that is the total width. And x_n and x_p you can express in terms of these doping dopant concentrations, and that is how you can write in terms of the built-in potential and the dopant concentration, and another quantity that you require is this is called permittivity ok; permittivity of the material.

And of course, what it means is the amount of charge needed to generate unit electric flux in a medium. So, basically, it says that what is the charge that you require to generate unit flux? So, that is permittivity. And individually, you can also write x_n is width multiplied by this fraction $\frac{N_A}{N_A+N_D}$ just the simple lever rule kind of expression and x_p will be $W\frac{N_D}{N_A+N_D}$. And you can see that x_n plus x_p will give you W only, and here we.

So, N_A and N_D; they are not necessarily equal right. So, they are differently doped on the same substrate material differently doped two materials are giving you two intrinsic semiconductors, and you are bringing them together ok. So, there is no mandatory thing that N_A and N_D will be equal, ok.

So, what we can write; that the x_n and x_p this expression the dependence on N_A and N_D is giving you an asymmetric width of the depletion region the across the junction. So, we can see the depletion region width is asymmetric across the junction in case N_A and N_D are equal a special case; of course, it is possible they are not mandatory equal, but they can be equal.

So, if they are equal then, x_n and x_p will be equal, and it will be symmetric, but that is a special case. It is not mandatory that they have to be so, please take that in mind. And this asymmetry

we can write extends deeper into the side of less doping. So, this is kind of counter-intuitive less doping side will be the depletion region width will be deeper ok.

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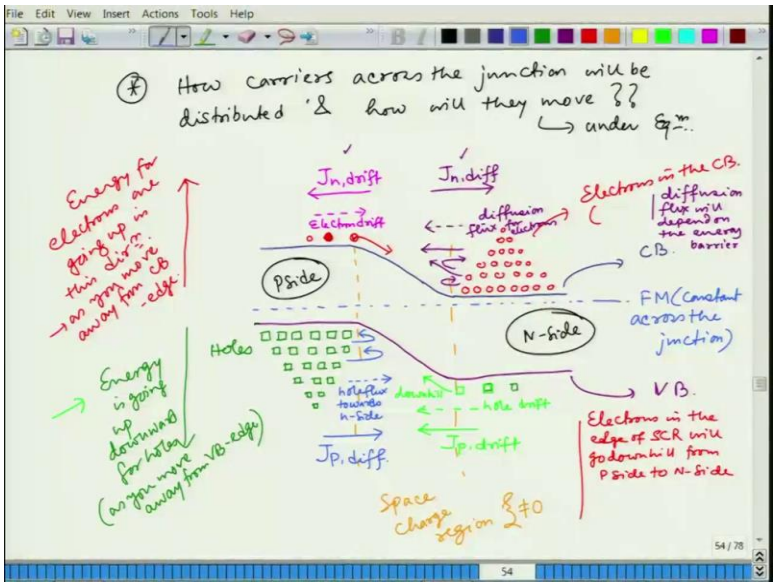

Now, let us ask these questions to ourselves like, ok. We have seen that across a p n junction, how a space charge region is created, how the distribution will be, and what would be the ratio of this carrier concentration across this junction ok. Now, how all of these will affect the scenario, or how will they affect the electron current density electron or whole current density? Let us look at that.

So, how carriers across the junction will be distributed, and how will they move right? So, that is the key to the photovoltaic effect. So, we have to understand that and let me urge you that you please pay close attention to see different things happening together. So, let us first draw the bent bands and the Fermi level. So, under equilibrium. So, for now, we are still under equilibrium.

So, the Fermi level will be constant. So, let me draw that first because that helps in keeping consistency. So, let us have that this is the Fermi level and let me write that that this is the conduction band bent and what color should I use this one maybe excuse my bad drawing, but yeah.

So, this is the Fermi level which is constant across the junction, and this one is the conduction band, and this one is the valence band ok. Now, we can see that here, on the left-hand side, we have the Fermi level close to the valence band; that means this is the P-side.

So, we can write this is the p-side, and on the other hand, the Fermi level is far away from the balance band and closer to the conduction band, so that is N-side ok. Now, you can see as you have Fermi level closure. So, electrons will be more easily available or more in concentration on the N-side. So, let us have these electrons, which are available in the conduction band more in the N-side, and as you go up from the conduction band edge, the concentration of electron will exponentially decrease.

So, let us say something of this sort, ok. So, it is all schematic; of course, we are just trying to understand how things will be affected. And similarly, for the P-side, we have a lot of holes, and again, in the valence band and again, the concentration of the same will decrease exponentially as you go away from the valence band, ok.

So, these are holes, and for holes, the energy is going up in this direction. So, energy is going up downward for holes, ok. So, basically, as you move away from the valence band edge right. And these are the electrons in the conduction band, and you have. So, here the energy for these one's energy for electrons are going up in this direction as you move away from the conduction band edge right.

And of course, so, these are the majority carriers electrons in the N-side and holes are majority carriers in the P-side, but of course, there will be minority carriers as well much less in number, but there will be minority carriers. So, what can you say? That on the P-side, you have few minority electrons. Let us say one or two in the conduction band. And similarly, in the N-side, you have one or two holes in the valence band, ok. So, now you can think of the currents, ok.

So, this is the space charge region right where the band bends. So, this is the space charge region where the field is not equal to 0, is not it, but the rest of the thing, even if you have a distribution of different charge carriers it is quasi-neutral region; this we discussed ok. So, think of the life of this particular electron, ok. Let us say this particular electron we are looking at we are sitting on that electron.

Now, due to random thermal motion, it will go here and there, and as long as it is in the quasi-neutral region, it will not effectively go in any direction, but such a wandering electron if it comes to this position where the field is not equal to 0 at the edge, it will be sucked in. So, this particular electron will be sucked into the other direction because you have a downhill direction in the energy. So, it will just go in the other direction, N-side, ok.

So, what we can write that electron in the edge of space charge region will go downhill from P-side to N-side, and that is what that motion is happening due to the field right; ξ is not equal to 0; that means it is going in the direction of field or the electron is going against the field. So, effectively what we are having is an effective electron drift motion, and that will give you a drift current.

And of course, whichever direction the electron goes, the current direction is opposite. So, what you can write $J_{n,\,drift}$ due to this it itinerant electron which was moving around, and as soon as it comes at the edge of the space charge region, it is sucked into the other direction in the other side N-side ok.

And similarly, if you think of the life of this the minority holes again, whenever it is coming towards the edge, it will be sucked in the other direction even if it looks like it is not going downhill, it is going as a Barfield, but for holes, we have seen that the energy is going up downward direction. So, again this is downhill for the hole, ok.

So, we will have and drift the whole drift from the N-side to the P-side, and effectively we will have a drift current, and now, whichever direction the hole moves, the current is in the same direction. So, what we can write this will be $J_{p,\,drift,}$ and this drift is only for the minority carriers.

On the N-side, it is the hole which is the minority carrier, and they are getting drifted due to this downhill energy in the space charge region right, and for the electrons, the downhill direction is for the minority electrons only which are coming from the P-side to the N-side ok. Now, look at the other thing, which is the diffusion current ok.

So, on the N-side, if you see that electron concentration is much higher than the P-side right. So, you have a concentration gradient across the space charge region from N-side to the P-side for the electrons, ok. So, as concentration is higher, there will be a diffusion current towards the P-side.

So, you can write that there will be a diffusion current diffusion flux for electrons, right. Now, all these diffusions all these electrons which are like gathered at the edge of space charge region in the N-side; all of them will not be able to cross the field region. So, for this electron, these electrons it is a field, right.

So, not all of them will be able to go few of them will there be random motion few of them will come back because they cannot cross the energy barrier and some of them will go to the other direction, and this diffusion flux will, of course, depend on the energy barrier ok. So, let me write here the diffusion flux will depend on the energy barrier; why? Because that will tell how many of them will be able to cross it and how many of them will not be able to cross it, ok.

So, again if you look at the diffusion current density, that will be $J_{n,\ diffusion}$ again, that will be in the opposite direction of the electron motion, ok. So, for the electron, for the electron, you have this diffusion current density and this drift current density ok. And similarly, the same thing will happen for the holes. So, let me use this particular symbol or color that holes again; will some of them will try and come back, and some of them will be able to go in the other direction, ok.

So, if I use a dotted line here, ok; some of them will go and what you have is this J_p; not J_p but hole flux towards n side and the majority carriers are going through this diffusive process, and minority carriers are going through the drift process ok. So, the effective value or effective contribution to the charge density or electron the current density will be $J_{p,\ diffusion}$ right.

So, please pay attention to this particular phenomenon, what is happening, how the diffusion and drift are happening, and which carriers are participating in what way ok. If you need you, please go back to this portion of the video again and try to assimilate the concept.

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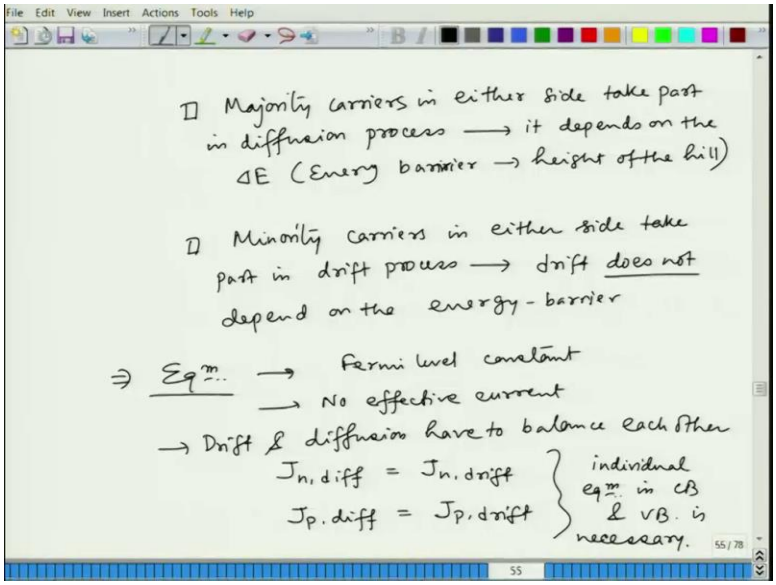

So, what we can write here few observations that majority carriers on either side take part in diffusion current or diffusion process right, not the minority carriers. And the diffusion process depends on the energy barrier or the height of the hill that it has to cross, which is the height of the hill, ok.

And on the other hand, the minority carrier, I should say yes, minority carriers on either side take part in the drift process; the drift process means what? It depends on the field, ok. So, the drift process; whenever an itinerant electron or hole comes near the space charge region edge, it is sucked into the other side.

So, that is drift, but that does not depend on what is the height of the hill. In downhill, you do not care how deep it is. When you are coming down, you can take a stair; you do not have to go through a lift, but when you are going up, it is difficult to climb the stairs; you can take a lift, or you should take a lift if you want to save energy.

So, these electrons and holes are also lazy in a metaphorical sense, of course, and they do not care when they are going downhill; they do not care about how deep it is. So, this drift does not depend on the value of the energy barrier. It is only the diffusion current that depends on the value of the energy barrier, ok.

Now, still, we have talked about equilibrium, and that is why we have kept the Fermi level constant ok. So, under equilibrium, we do not have any effective current right. So, no effective current. So, whatever is happening with this drift and diffusion, they have to balance each other under equilibrium, is not it?

So, drift and diffusion have to balance each other, and not only the overall current density has to be matched; it has to be matched in either conduction band or in valence band right. o, electron there should be no effective transfer of an electron from any side and similarly for the holes.

So, individually there has to be equilibrium both in the conduction band and in the valence band. So, what you can write that for the conduction band, this $J_{n,\text{ diffusion}}$ is nothing, but $J_{n,\text{ drift}}$,

then only if they have the same magnitude and they are opposing each other. So, basically, there will be equilibrium or no effective transfer.

And similarly, for the valence band, you have this equality of magnitude for the whole current diffusion current and drift current, and again, you will see that they are in opposite directions. So, here you see here that the J_p in diffusion and $J_{p\ drift}$ are in the opposite direction.

So, they have to match each other in magnitude, and here also, for $J_{n\ diffusion}$ is opposing the $J_{n\ drift}$. So, again their magnitude has to be equal, ok. So, this is individual equilibrium in the conduction band and in the valence band is necessary right.

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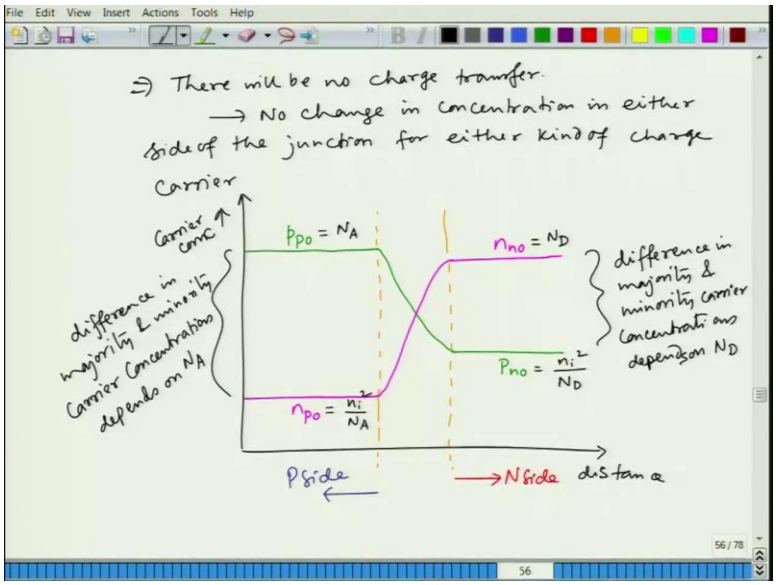

And their equality is giving you the equilibrium condition that no effective transfer of charge. Now, what will happen to the concentration profile, ok? So, under equilibrium, there will be no charge transfer. So, whatever is drifting to the for electrons, whatever is drifting to the N-side, it has to be matched with the whatever is diffusing to the N-side P-side.

So, basically, no charge transfer, no change in concentration on either side of the junction for either kind of charge carrier. So, both electrons and holes; will be the concentrations will be maintained at the same level all the time, ok now, if we want to look at how this will change, ok.

So, let us say that this is the carrier concentration in this direction. It can be an electron or hole, and this is the distance. So, let us say the space charge region is here; let me use another color space charge region is here. So, what you can write that and this is the P-side, and this is the N-side, yeah. Now, on the P-side, you can say that the majority of carriers will be holes ok. So, we have a large value here, which is p_{po}. So, under equilibrium, what is the whole concentration in the P-side?

And similarly, on the N-side, it will be a much less value of holes. So, we can write it P_{no}. So, and now for the electrons, it will be the majority carrier on the N-side. So, it will have to have

some value greater than the minority carrier. So, let us say this is the value in the N-side, the electron concentration value under equilibrium ok.

And on the other hand, on the p-side, the electron will be a minority carrier it will have less amount. So, this is sorry; this is n_{po} right. And in between, there has to be continuity in the space charge region.

So, the hole concentration should come down like this, and the electron concentration should go up like this right. So, that will the under equilibrium, and that will be the typically the scenario of concentration in two sides. And now, you also know how to quantify them right.

So, p_{po} you have seen that it is dependent on the acceptor dopant concentration and the, for the N-side, the majority carrier depends on the donor dopant concentration N_D ok and the ratio of the majority and minority carrier that we obtained from the equation of.

So, this n_{po} will be equal to n_i square divided by N_A, ok. Acceptor dopant concentration is only relevant in P-side ok. So, that will depend on n_i squared by N_A, and here, on the N-side, the minority carrier concentration will depend on n_i squared by N_D, ok.

So, you will get this information that I am writing in the plot from these relationships, ok. So, that is how we are getting these concentrations. So, here you note; that on the N-side, this difference in the majority and minority carrier concentrations depends on N_D or the donor dopant concentration.

And on the other hand, on the P-side, the same thing; that means the difference in the majority and minority carrier concentrations depends on N_A ok because that is the P-side and acceptor dopant concentration is what determining the majority and minority carrier ratio ok.

So, that is how this junction P n junction is working internally under equilibrium; what are the concentrations and how the electrons and holes will diffuse and drift and balance each other that we have seen today. So, in the next class, what we are going to look at is the non-equilibrium condition. If you apply some voltage, if you apply some potential, how this whole thing changes; that is what we are going to look at in the next class.

Thank you for your attention.