Elements of Solar Energy Conversion
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Lecture - 33

Hello everybody, welcome back to the series of lecture on Elements of Solar Energy Conversion. We are now, looking at the photovoltaic conversion mechanism and we are here at lecture 33. So, in the last class where we stopped, we were discussing the concentration of majority and minority carriers across a P-N junction, ok.

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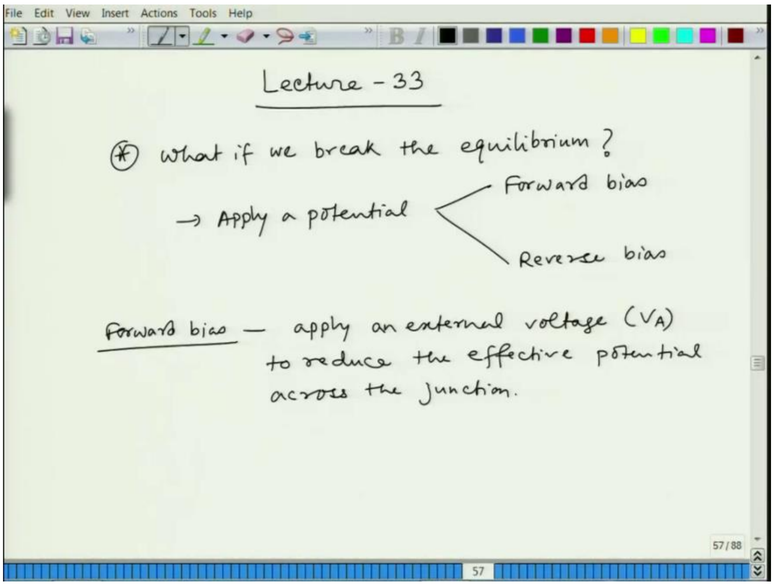

And we have looked at how the energy barrier will affect the diffusion current, but not the drift current, ok. And then, how the equilibrium concentration across the P-N junction diode will depend on the energy barrier that we have looked at. So, today we are going to start if we now break the equilibrium, ok.

So, equilibrium is the good thing to be at, but it is useless, because you cannot get anything out of it, it is a status quo. So, if we want to get some current out of the photovoltaic material, we have to break the equilibrium and now, we are going to look at how breaking the equilibrium will affect this whole scenario across the P-N junction.

So, what if we break the equilibrium? So, how to do that? The best way to do it is applying a potential and the easiest way to do it as well. And whenever we talk about potential, it has a direction, right. So, you can have forward bias, that means, you are enhancing or you are decreasing the energy barrier across the P-N junction and it can be reverse bias, ok.

For this condition, bias means the external potential applied. So, now, we have to look at how this forward biasing or reverse biasing will affect the P-N junction. So, forward bias means, that you apply an external voltage. Let us call it V_A, A stands for applied to reduce the effective potential across the junction, ok. So, how will the physical picture look like?

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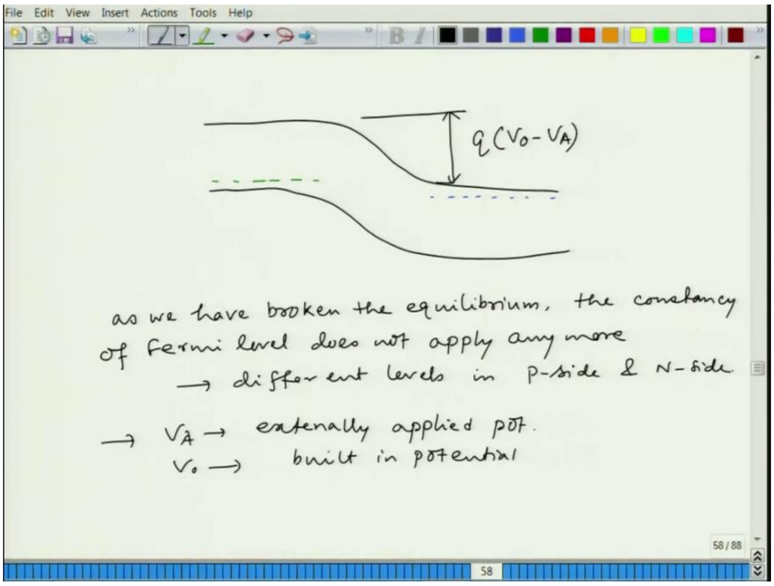

So, you have this thing. Now, you have reduced it to a lower value. So, basically this is the potential barrier or equilibrium, we call it built in potential. Now, we have this energy barrier, which is less than the built in potential, because we have applied the potential in such a direction that the effective potential gets reduced and that is called forward bias. And now, as we have broken the equilibrium, we are no longer under the restriction of constancy of fermi level, ok.

So, we can have fermi level at different levels in different parts of the junction or across the junction. So, now, what we can say that, as we have broken the equilibrium, the constancy of Fermi level does not apply anymore, ok. So, now, you can have different fermi levels in the P side and N side.

And you can see that this V_A is the externally applied potential and V_0 is the built in potential, which is present even in case of equilibrium, ok. So, forward biasing means that you reduce the energy barrier by applying the external potential, this is important to know.

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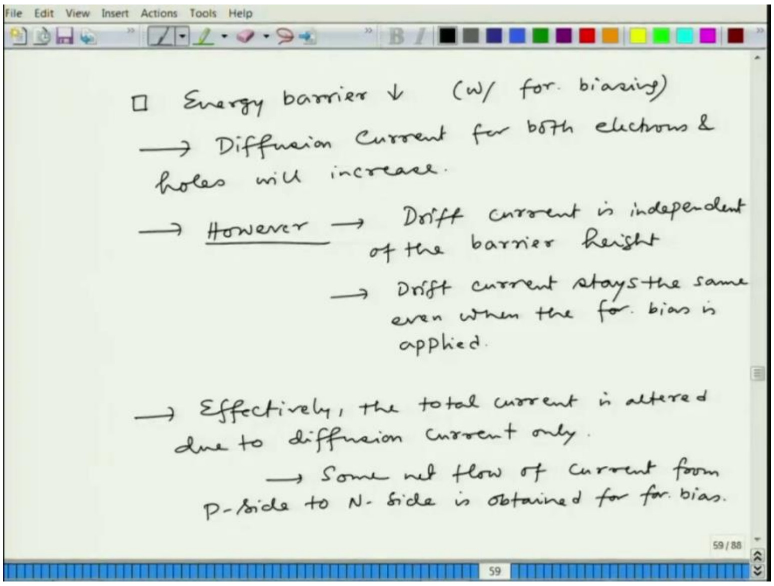

So, now as the energy barrier decreases with forward biasing. So, with forward biasing, the diffusion current for both the carriers, both the electrons and the holes will increase, because we have seen that the energy barrier dictates the diffusion current magnitude, ok. So, diffusion current will increase, however, the drift current is independent of the barrier height, is not it? This we discussed in the last class.

So, if drift current is independent of the barrier height whatever potential forward bias you apply it does not alter the drift current. So, drift current stays the same even when the forward bias is applied, ok. So, now, the total current is summation of the drift current and the diffusion current, right.

So, one part is invariant, it is not changing with the biasing, but the other part is getting increased for forward biasing. So, effectively the total current is altered due to diffusion current only, ok. So, that is the effect of the forward biasing, when you break the equilibrium. Now, you have increased diffusion current and so some net flow of current from P side to N side is obtained for forward bias, ok.

So, under equilibrium what we have seen that, even if there are drift current and diffusion current in the microscopic level, but effectively you did not have any net flow of holes and electrons, ok. The drift and diffusion were balancing each other, but now that balance is broken, the equilibrium is broken. So, you will have a net flow from P to N side for forward biasing.

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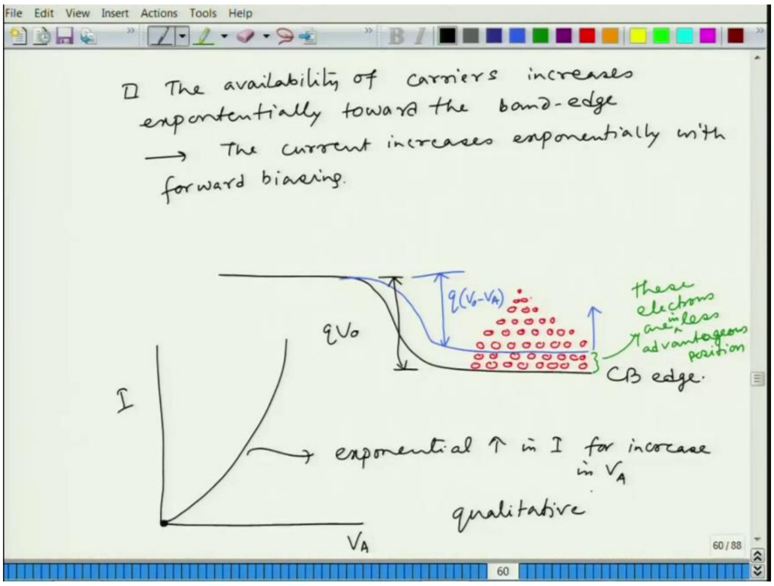

Now, you can think of the availability of carriers increases exponentially towards the band edge, right. So, if you go closer to the conduction band, the electron concentration will increase exponentially. And similarly, if you go closer to the valence band, the hole concentration will go up exponentially, right.

So, if that is the case the current increases exponentially as well with forward biasing. So, let me draw a quick schematic you can think of. So, let say only for electron, this was the case earlier. Now, what we are doing? Let us keep this part same and now, we have reduced the height of the energy barrier, ok. So, $q(V_0 - V_A)$ is the energy barrier now, and earlier it was qV_A, right. So, this is the case under forward biasing.

Now, you can think of the electrons. So, let us think of a stack of electrons which are decreasing as you go away from the conduction band edge. This is the conduction band edge, right. So, you can think of when the forward bias is applied, so, more number of electron are above that level, ok.

So, starting from here, all the electrons can now move to the other side if they can overcome the energy barrier, ok. So, this is of course schematic. Do not count the number of electrons here. So, these electrons are in less advantageous position compared to the top ones, ok; that means, they will face difficulty in moving to the other part.

So, that is why current will increase exponentially as the forward biasing voltage (which is V_A) is increasing. So, what we will get you can think of, if we draw I versus the applied voltage V ok, we can think of the current will increase exponentially with forward biasing, ok.

So, this is exponential increase in current for increase in applied forward bias and what is happening here at the origin? When $V_A = 0$, that means, you are only under equilibrium, because it is V_0, that is the built in potential across the junction and under that equilibrium you do not have any net current. So, I = 0, right.

So, starting from 0, as V_A increases in the forward bias direction your current is increasing exponentially, ok. So, we are talking about now is qualitative, it is important to know. So, this is qualitative, we will come to the quantitative part once we get the concept cleared in terms of qualitative understanding.

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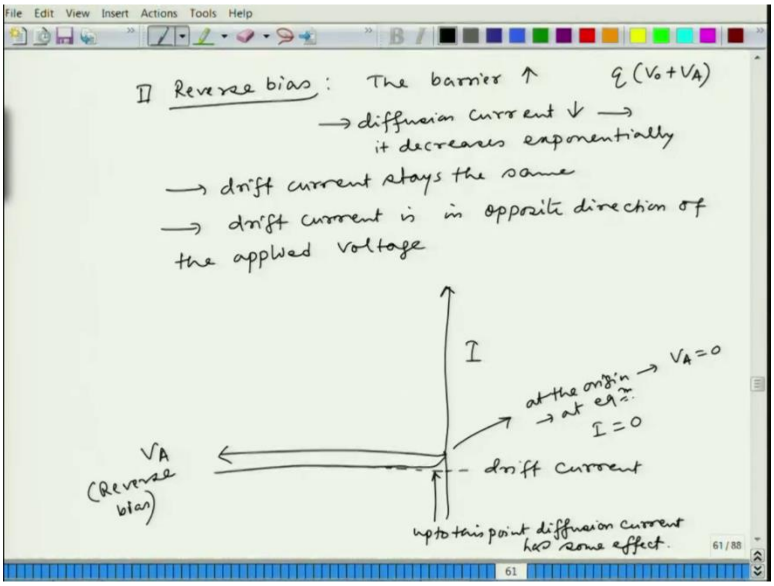

And the interesting thing happens when you apply a reverse bias. So, under the reverse bias what you are doing? The barrier you are basically increasing. Now, the barrier will be q $(V_0 + V_A)$, ok. So, the applied voltage is working in such a direction the barrier height is actually increasing, ok. So, that means, the diffusion current decreases, but more importantly it decreases exponentially. So, for a very small value of V_A if you increase the drop will be very drastic, ok.

So, for a reasonably large value of V_A it will go to basically 0 right, because the drop is so, fast. And on the other hand, drift current stays the same. Drift current is not changing with the barrier height, it did not change for forward bias, it does not change for the reverse bias either, ok. And this drift current is in the opposite direction of the applied voltage, right.

Drift current is always downhill. For the electrons in the conduction band, it has to go downhill in the space charge region and that is in the opposite direction of the applied voltage now. Now, applied voltage is from N side to the P side that is why we call it reverse bias, right. So, what we can expect? Now, we are drawing it in this direction. So, let say this is the reverse bias. So, it is in the opposite direction of the forward bias.

And the diffusion current decreases very fast as you go up in the reverse direction. So, you can think of up to this point, diffusion current has some effect and beyond that it becomes negligible.

So, drift current which stays even under reverse bias, but in the opposite direction, ok. And at the origin, what is happening? At the origin, again the $V_A = 0$ that means you are still at equilibrium. So, overall current will be 0, right.

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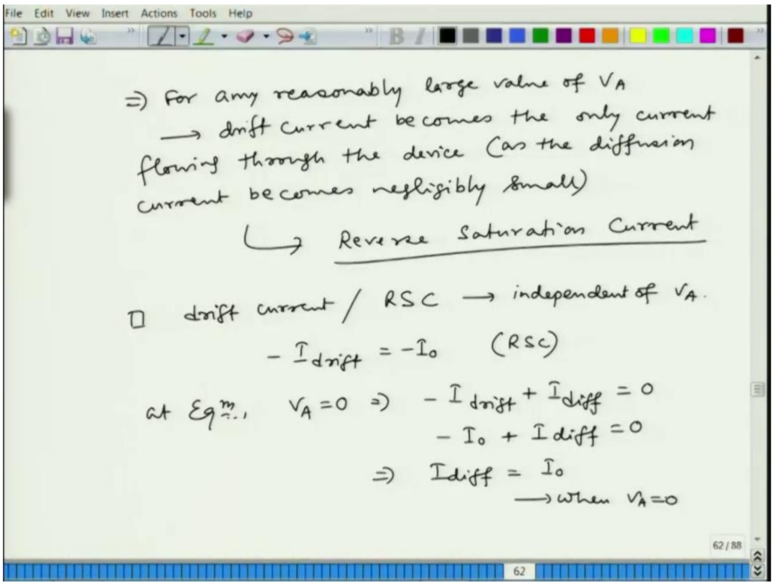

So, for any reasonably large value of applied voltage, the drift current becomes the only current flowing through the device as the diffusion current becomes negligibly small, ok. Now, this value of drift current that is independent of the bias we call it reverse saturation current, ok.

Why reverse saturation current? Reverse is for under the reverse bias and saturation is that is the value it saturates too; it does not change anymore with the change of applied voltage. So, basically the current reaches a saturation level that is why it is called reverse saturation current.

Now, this reverse saturation current is independent of the applied voltage or the bias. So, what we can write?

$$-I_{drift} = -I_0$$

naught means it does not depend on the applied voltage and reverse saturation current, and why negative? Because it is opposite to the direction of applied voltage, ok.

Now, at equilibrium,

$$V_A = 0$$

So, in that case,

$$-I_{drift} + I_{diff} = 0$$

I_{diff} is the net current due to diffusion will be towards the applied voltage from p to n, ok. Now, at equilibrium these two will be equal to 0. So, now, if we put this $I_{drift} = I_0$, that means, the I_{diff} at equilibrium is equal to the same value which is the reverse saturation current, ok.

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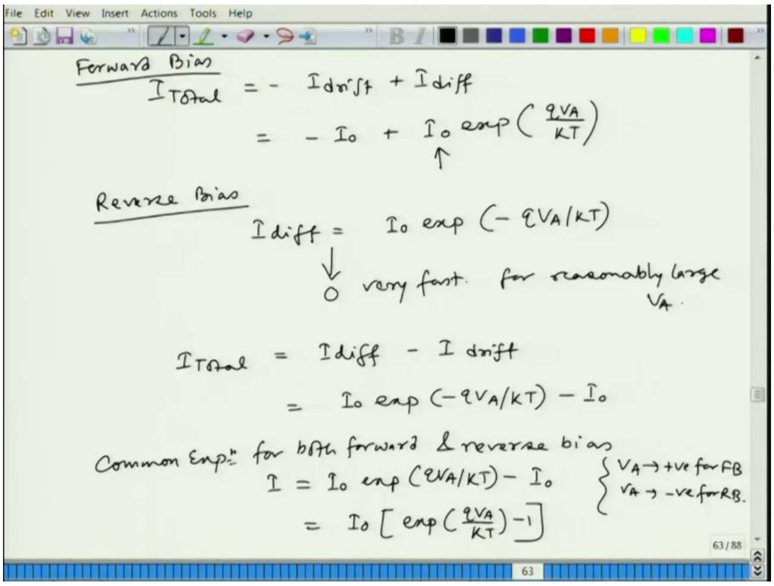

So, under forward bias, we can write,

$$I_{total} = -\, I_{drift} + I_{diff}$$

$$I_{total} = -I_0 + I_0 e^{\frac{qV_A}{kT}}$$

Under forward bias, what we have? Again, we have drift current which is opposite to the applied voltage in the direction and diffusion current is towards the applied voltage.

And that depends on the applied voltage in this fashion, ok. This I_0, how do we get? This is corresponding to V = 0, right. So, $I_{diff} = I_0$, when $V_A = 0$, ok. So, that is the pre-exponential function or factor that we are getting in the expression of I_{diff}, ok.

So, that is the expression of current under forward bias. Now, what we will get under reverse bias? So, I_{diff} is again the same form we can use, but now with a negative sign right, because it is in the opposite direction. Now, this whole thing drops to 0 very fast for reasonably large V_A, ok.

So, what we get? I_{total} is again,

$$I_{total} = I_{diff} - I_{drift}$$

$$I_{total} = I_0 e^{-\frac{q\,V_A}{kT}} - I_0$$

So, you can see that in both the cases for forward bias and reverse bias, we get the same expression back and what is that expression?

So, the common expression for both forward and reverse bias is,

$$I = I_0 e^{\frac{q\,V_A}{kT}} - I_0$$

where this V_A is positive for forward bias and V_A is negative for reverse bias and you can write,

$$I = I_0 \left[e^{\frac{q\,V_A}{kT}} - 1 \right]$$

So, that is the common expression we get whatever voltage we apply. So, the direction will come into play in the formulation, ok.

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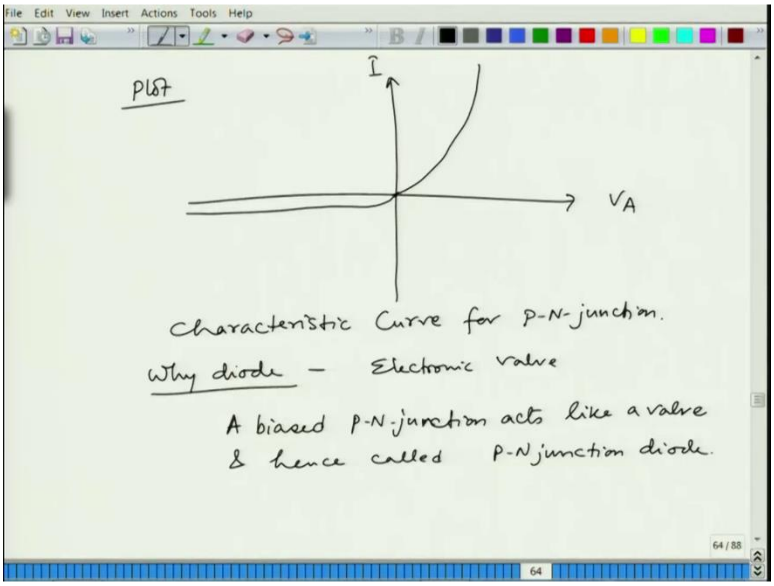

So, now, if we plot this common function, how will it look? In this direction we have I and in this direction, we have V_A (applied voltage). So, you have seen the forward bias part will be like this right and the reverse bias part will continue and we will have a constant reverse saturation current I_0, ok.

So, this will be the form of the V-I characteristic curve for a P-N junction diode, ok. So, this is called characteristic curve for P-N junction. And this curve will tell you why it is called a diode, ok. So, why diode? Diode (by definition) is an electronic valve which allows flow in one direction, but not the other direction.

So, you can see from this characteristic curve itself that in the forward bias direction it allows current, but in the reverse direction it does not or it does very little which we can neglect that is why it is called electronic valve or diode, ok. So, a biased P-N junction acts like a valve and hence, called P-N junction diode, ok. So, that is the reason.

Now, so far, whatever we have discussed is all qualitative not very quantitative. We do not know what is this reverse saturation current, it is just an arbitrary symbol we have used I_0, but we need to find that out quantitatively in terms of other material properties, this doping concentration and all, ok.

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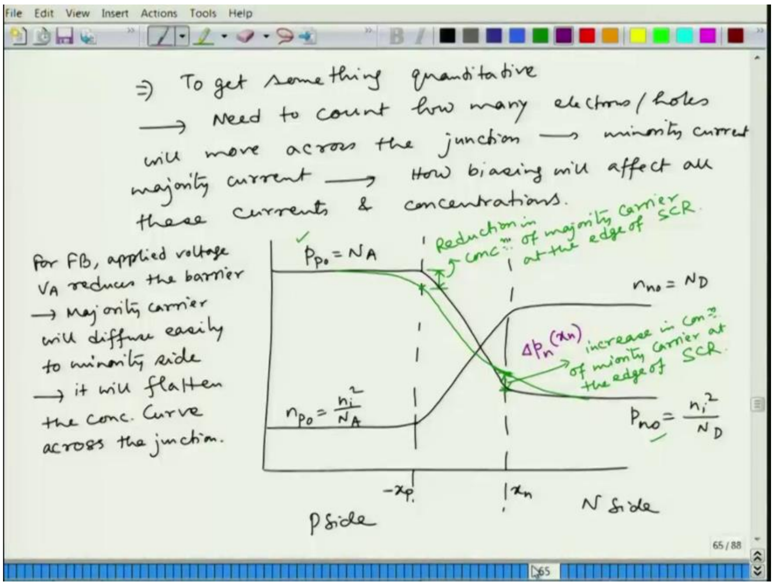

So, to get something quantitative what we require? We need to count how many electrons or holes will move across the junction, is not it? Which will tell us what would be the minority carrier current, majority current and so on. And most importantly, how biasing will affect all these currents and concentrations, ok.

So, let us now, look at it. So, earlier we have seen that if you plot the carrier concentrations across the P-N junction, it will look somewhat like this. This is for the holes. This is the P side and this is N side. So, this is for the hole, $p_{po} = N_A$, this is under the equilibrium right now, I am showing you. This you have seen earlier also.

And this is, $p_{no} = \frac{n_i^2}{N_D}$, this is under equilibrium and that is why we are using this subscript naught. And for the electrons, you will have something like this, where you will have $n_{po} = \frac{n_i^2}{N_A}$ and the other side $n_{no} = N_D$.

Now, when we apply a forward bias so, how will the things change? Let me look at just for the hole part, ok. So, let me write here for forward bias applied voltage V_A reduces the barrier that means the majority carrier will diffuse easily to minority side and the effectively, what it will do? It will flatten the concentration curve across the junction.

Same thing, we can do for electrons, but let us look at hole itself. So, hole is the majority carrier in the P side. So, hole is the majority carrier you can see the concentration is much larger there and in the N side it is minority carrier, and the concentration is much less.

Now, due to forward bias what will happen? The curve will flatten that means, you will have some reduction of majority carrier concentration at the space charge region edge here. So, here you see a reduction in concentration. Reduction in concentration of majority carrier at the edge of space charge region and similarly, you have an increase.

So, the curve is flat flattened. So, you have some effective increase. So, increase in concentration of minority carrier, because in the N side holes are the minority carrier. So, increase in concentration of minority carrier at the edge of space charge region that is what the result of a forward bias will mean. Now, we need to quantify this decrease or increase at the space charge region, because that will tell what would be the effect on currents?

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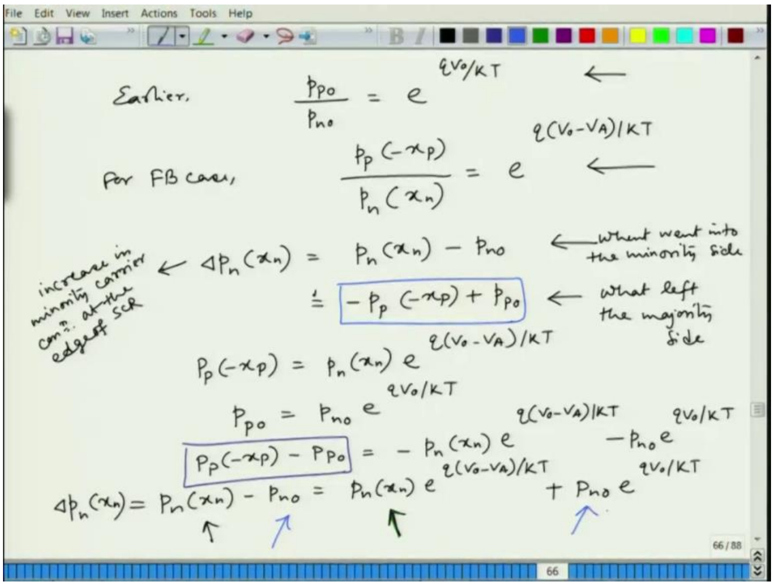

So, earlier what we have seen is this under equilibrium what are the ratio of carrier concentration across the space charge region, ok. So, hole concentration ratio between P side and N side is,

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

And here in this figure, let me write that this is our $-x_p$. This we have designated as space charge region width, one side it is the coordinate is $-\ x_p$ and the on the other side it is x_n, ok.

So, what we can write for forward bias case, this p_p, that means, holes in the P side and at the location of minus x_p which is the space charge region edge in the P side divided by the holes in the n side; that means, in the minority direction at x_n which is the space charge region edge in the N side this is equal to $e^{\frac{q\,(V_0 - V_A)}{kT}}$, right. So, the curve flattening whatever we talked about in the last figure, now, we are quantifying in the form of forward biasing, ok.

So, now we can say that this change in hole concentration in the minority side, in the space charge region is nothing, but $p_n(x_n)$ right minus what it was under the equilibrium. So, basically, we are saying that this increase is $\Delta p_n(x_n)$ and one thing I should tell you here that the forward biasing is doing what? It is reducing the concentration in the majority side and increasing it in the minority side at the cost of it, ok.

But the effect is much more relevant for the minority side, because in the minority side you have very less concentration of that particular carrier. When you are in increasing, it its effect is much higher, but where you already have a lot you take some of it does not matter, it is just like a very rich man if he gives certain amount of money to a very poor man. So, for the rich man it does not matter at all right, but for the poor man the same amount of money will make his life very different.

So, here also in the majority side the reduction is concentration is not affecting the overall scenario, but in the minority side that increase is very important and that is what we are trying to understand here. So, this is what? This is basically the amount that went into that poor man’s pocket, ok.

So, that is what we are trying to quantify. This is the increase in minority carrier concentration at the edge of space charge region and we are doing everything for the holes and the same thing can be done for the electrons. So, we are not going to repeat it, we will go step by step for the holes and then once we obtain the final expression, we can use the counter part of it for the electrons, ok.

So, for the conservation of number of electrons or holes, we have to have balance from the majority side, ok. So, you can think of what left the majority side and this is what went into the minority side. So, they have to be equal to each other, whatever the rich man lost the poor man gain the equal amount that is why this equality holds.

So, now, from this what we can write this,

$$p_p(-x_p) = p_n(x_n)\, e^{\frac{q\,(V_0 - V_A)}{kT}}$$

So, the same thing we can write for p_{po}. Now,

$$p_{po} = p_{no} e^{\frac{q\,V_o}{kT}}$$

So, now, if we write,

$$p_p(-x_p) - p_{po} = -p_n(x_n)\, e^{\frac{q\,(V_0 - V_A)}{kT}} - p_{no} e^{\frac{q\,V_o}{kT}}$$

So, now this $p_n(x_n) - p_{no}$ is nothing but, negative of this quantity, right. So, if you look at this quantity, and this particular quantity it is just the negative of each other, right.

So, what we can write is this thing,

$$p_n(x_n) - p_{no} = p_n(x_n)\, e^{\frac{q\,(V_0 - V_A)}{kT}} + p_{no} e^{\frac{q\,V_o}{kT}}$$

So, this is our money that went into the poor man's pocket, the increase in minority carrier concentration.

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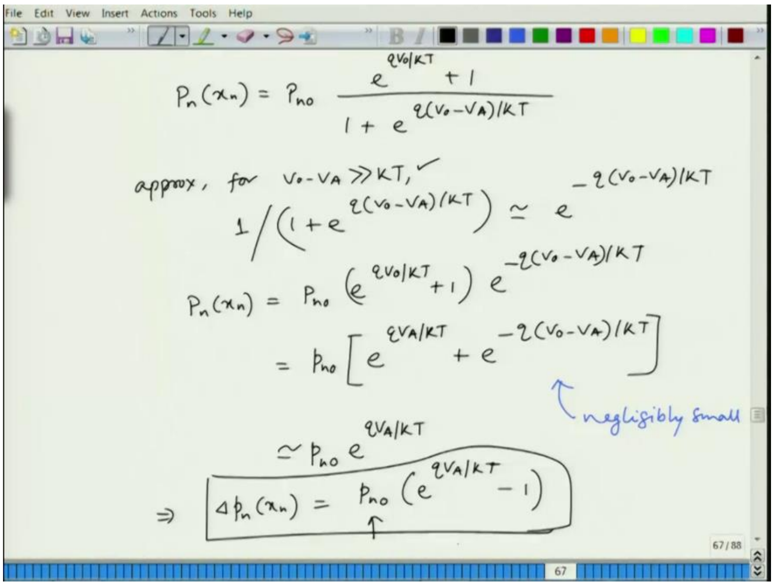

Now, this $p_n(x_n)$, we have seen that we have in the expression of this delta $\Delta p_n(x_n)$. We have this $p_n(x_n)$ that we have to first find out. So, now, what we are doing is we are using or collecting this $p_n(x_n)$ in one side and expressing it in terms of p_{no}, ok.

So, these two you are collecting and these two you are collecting together, right. So, $p_n(x_n)$ you can write,

$$p_n(x_n) = p_{no}\,\frac{e^{\frac{qV_0}{kT}}+1}{1+e^{\frac{q\,(V_0-V_A)}{kT}}}$$

Now, we will use the approximation that, $(V_0 - V_A) \gg \mathrm{kT}$, what we can write,

$$\frac{1}{1+e^{\frac{q\,(V_0-V_A)}{kT}}} \approx e^{\frac{-q\,(V_0-V_A)}{kT}}$$

This particular assumption is more or less true for any reasonable temperature. If you are not considering very high temperature, this is true.

$$p_n(x_n) = p_{no}\left(e^{\frac{qV_0}{kT}}+1\right)e^{\frac{-q\,(V_0-V_A)}{kT}}$$

So, now, what you can do? You can do a little bit of algebraic manipulation to get this particular quantity,

$$p_n(x_n) = p_{no}\left[e^{\frac{q\,V_A}{kT}} + e^{\frac{-\mathrm{q}\,(V_0 - V_A)}{\mathrm{kT}}}\right]$$

So, if you do that you will see that this part is negligibly small, because it is a negative exponent, right. So, what you can write,

$$p_n(x_n) \approx p_{no}e^{\frac{q\,V_A}{kT}}$$

So, here we see that the built in potential is completely went off the table, ok. So, this will give us,

$$\Delta p_n(x_n) = p_{no}\left(e^{\frac{q\,V_A}{kT}} - 1\right)$$

This is a very important relationship, ok.

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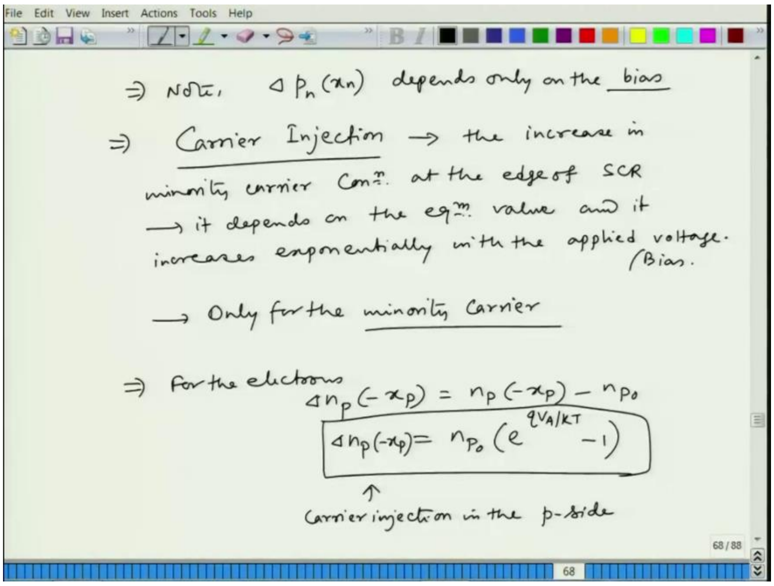

So, note that this $\Delta p_n(x_n)$ depends only on the bias, right. The forward bias in this case, but it is depending on the bias itself not the built-in potential, ok. And what is this? This is called carrier injection. So, basically you are injecting some carrier into the minority side, right. So, this carrier injection is nothing, but the increase in minority carrier concentration at the edge of space charge region, ok.

And it depends on the equilibrium value right, we have seen that it depends on this equilibrium value and the applied voltage, and it increases exponentially with the applied voltage or what we called bias. And it is only for the minority carrier, ok.

Whatever decrease happens, because of this in the majority side, we do not care about it. So, it is important to remember that carrier injection does not happen for the majority carrier, ok. And the same thing we can do for the electrons, we can write this Δn_p, of course, p stands for the P side.

So, increase in electron in the P side, that means the minority carrier and at the space charge region edge which is in the P side, it is,

$$\Delta n_p(-x_p) = n_p(-x_p) - n_{po}$$

And we can show in similar way, it will depend on $n_{po}\left(e^{\frac{qV_A}{kT}} - 1\right)$.

So, this is the carrier injection in the P side. So, now, we have quantified the effect of bias in the carrier concentration and particularly for the minority side or minority carriers. So, let us look at its implication in terms of current in the next class.

Thank you very much for your attention.