Solar Photovoltaics: Principles, Technologies and Materials

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Lecture – 23
P-N Junction Analysis (Light)

So, welcome to this new lecture of Solar Photovoltaic: Principles, Technologies and Materials. And we were discussing this P-N Junction Analysis in light. So, before we go to the continuation of previous lecture, we will just recap the previous lecture.

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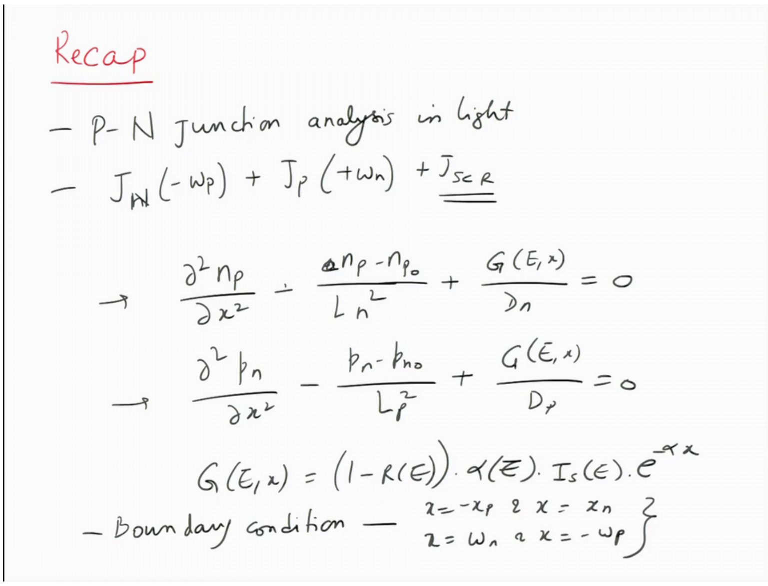

So, in the previous lectures, we in the previous lecture, we started our discussion on so we so we started our discussion on P-N junction analysis in light. And in these conditions, what we want to calculate is a J N at J N at minus w p, plus J p at plus w n plus J SCR, because this J SCR is now finite, because you have certain amount of recombination as well as generation within the semiconductor.

And we also made various other assumptions to calculate currents. And basically we needed to solve the minority carrier equations, the carrier equations were del 2 n p by del x square minus delta n p divided by so we can say n p minus n p naught divided by L n square plus G E, x divided by D n. So, sorry let me there should be E, x divided by D n is equal to 0.

And then we looked at del 2 p n del x 2 minus p n minus p n naught divided by L p square plus G E, x divided by D p that is equal to 0. So, one is for electrons and another is for holes, both are minority carriers. And where we looked at G E, x or I think it was small G E, x which was equal to 1 minus R E into alpha E into I s E, which is the incident radiation into e to the power minus alpha x.

This was the these were the equations with which we started and we also make certain boundary conditions. And those boundary conditions were boundary conditions; boundary conditions and boundary conditions were at x is equal to minus x p as well as x is equal to x n. And then the boundary conditions were at x is equal to w n and x is equal to minus w p.

So, at x is equal to minus x p and x n, we considered the surfacery combination into account, whereas x is equal to w n and minus w p we just took the same concentration of carriers that we took earlier. And that was n i square divided by n d exponential of q V a minus by k T minus 1 for electron hole concentration and for electrons, it was n i square divided by n a into exponential to power q y q V by k T minus 1.

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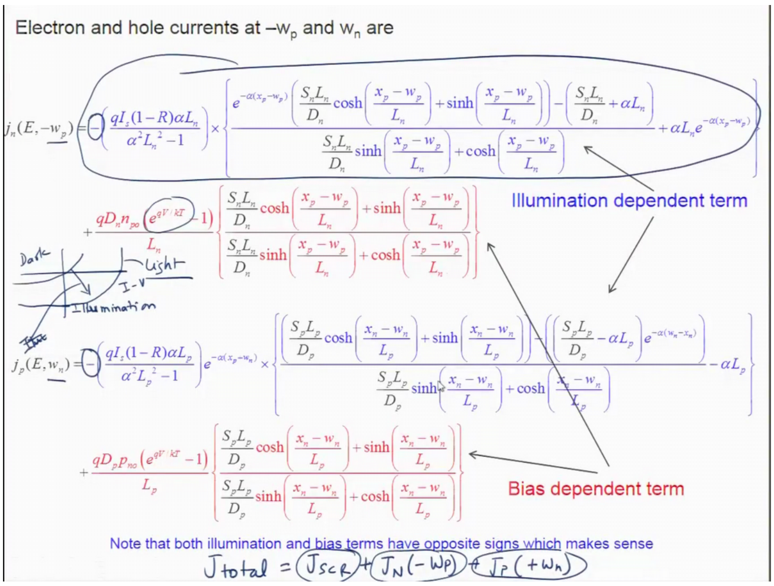

So, this was the these were things that we did. And if you look at those expressions, we said in the last go back to the previous lecture. So, we looked at these expressions for electrons and holes and what we came up with these was something like this. So, we had these electron concentration sorry the electron current at minus w p as a function of energy.

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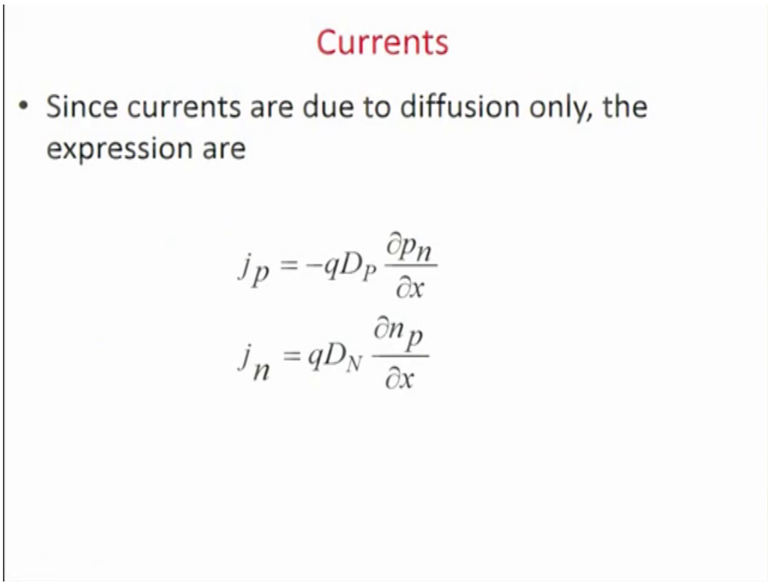

And then hole current at plus w n, and we what we got was we had two different so this was what the differential equations. And when we substituted these carrier concentrations into these differential equations, what we got is the current. And this current is basically you can see there is a bias dependent term, there is a illumination dependent term, both are independent of each other.

So, one depends upon the incident radiation and second depends upon the bias. Similarly, here one depends upon the incident radiation, another depends upon the bias. So, this is I s here in both the terms, similarly you have q V by k T. So, obviously if you make the I equal to 0, it should take us back to the P-N junction in dark, so that should be doable. So, I will leave that to you exercise that what happens when you take, when you make the illumination equal to 0, then P-N junction should work like a P-N junction in dark.

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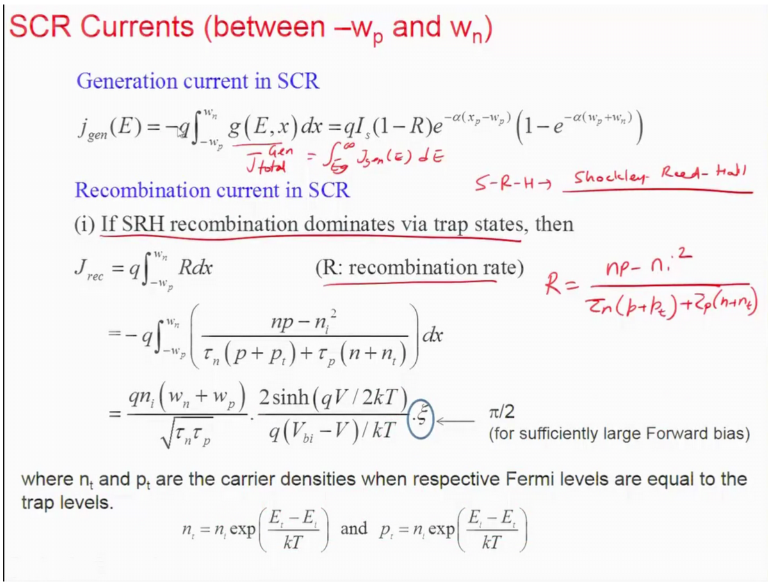

So, this is what the total current was and then we did these analysis for SCR current. The SCR current since there is generation, we have a generation current and we have a recombination, we have a recombination current.

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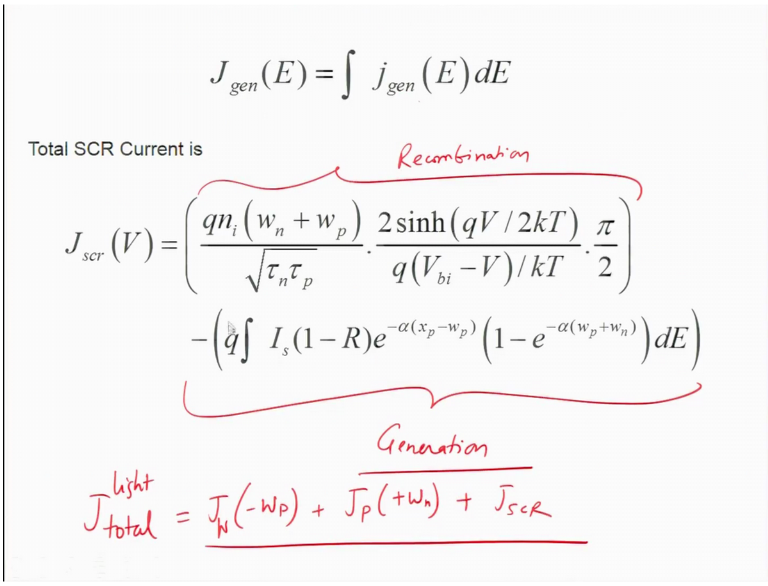

And mathematical sum of these two will give us the SCR current. SCR current is the current because of recombination minus the current because of generation. So, generation current will be negative, whereas recombination current will be positive. So, basically the in the light total current is J N at minus w p plus J p at plus w n plus J SCR.

And this is what is total current, which is simplified by making a few assumptions to make them suit to the practical solar cell diodes.

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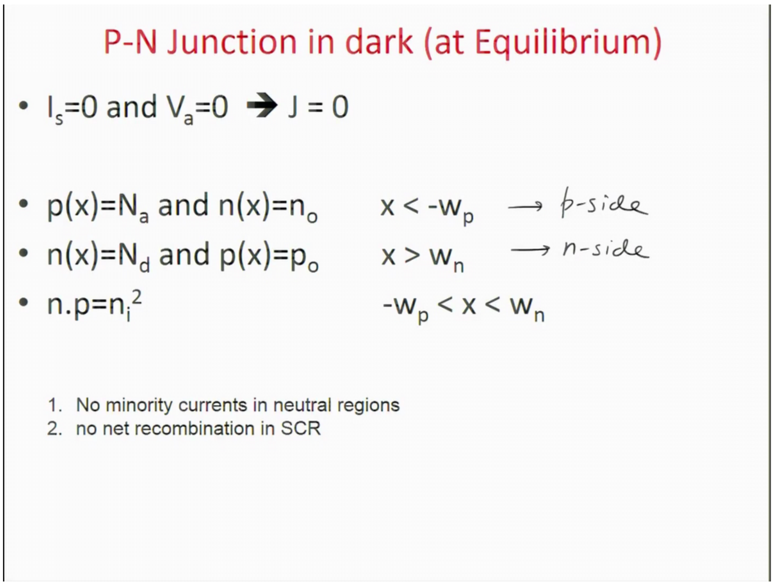

And we will now get back to our current lectures this thing. As in the current lecture, we look at a few special cases to solve these equations ok. So, the first special case that we look at is P-N junction in dark that is at equilibrium, of course I s is equal to 0, V a is equal to 0, which means J should also be equal to 0, which is perfectly fine and if we do that you will find that.

And then of course, p x is equal to N a and n x is equal to n naught for x less than minus w p. And n x is equal to N d and p x is equal to p naught that is so this is on the p-side, and this is on the n-side. So, basically it should look like a P-N junction in dark at equilibrium without any biases and without any illuminations. So, both the equations which I showed you earlier they should boil down to this. And of course, between x p and between w p and w n, n p is equal to n i square. So, basically no minority currents in the neutral regions and no net recombination in space charge region that is what the assumption was.

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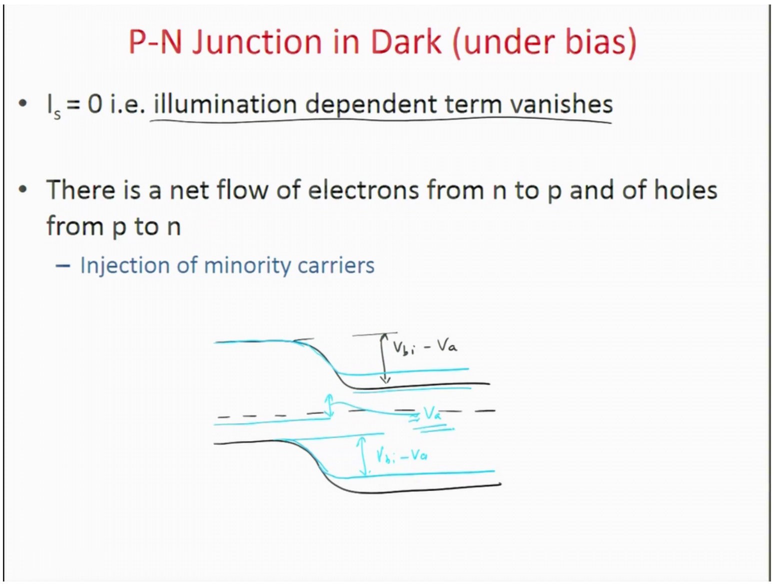

Now, if you have a P-N junction in dark under applied bias, then of course I s is equal to 0 that is the illumination term vanishes. So, there is no illumination term, what we are left with is only the current term. So, there is a net flow since, you have a bias which means in the moment you have bias, you have situations like in the previous case basically there was no bias, but now you have a bias.

So, if you look at the P-N junction, the P-N junction has a profile like this. So, when you have no bias, then Fermi levels are aligned and you have a built in field all right. When you apply bias for positive bias, it becomes V b i minus V a, which means the Fermi levels are also split.

So, when the bias is applied, these Fermi levels are if I use a different colour, so when the bias is applied, the levels becomes something like these all right so ok. And here also it will increase by certain level. So, essentially this bias has now reduced to V b i minus V a which means the Fermi levels also. We can see that there is a shift in Fermi levels level also, Fermi levels are going to going to split. So, since the energy levels have region on this side, then n Fermi level goes here and p Fermi level goes here. So, there is a split and that split is equal to the applied bias all right. So, basically the Fermi levels I split, and this split is nothing but equal to V a.

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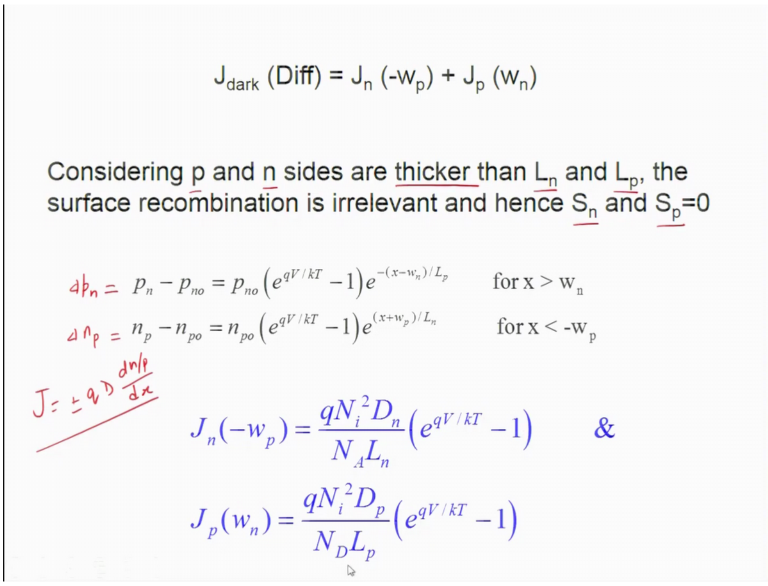

So, now there is a split in the Fermi levels, as a result you will have so what you will do is that you use J dark as a consequence of diffusion will be equal to J n minus w p plus J p at w n. Considering and we also consider that n side and p sides are thicker than so considering that p and n sides are thicker than L n and L p, which means the semiconductor diode is thicker than the diffusion distance of minority carriers.

As a result surface recombination becomes irrelevant, because the carriers will recombine by the time they reach the surface ok. So, it is a basically long biased diode, you can say diode is pretty long. As a result you can write for x greater than w n your p n minus p n naught is equal to p n naught into exponential of q V by k T minus 1 into exponential of minus x minus w n divided by L p, this is for this can be so the previous equations are simplified now ok.

So, since surface recombination is irrelevant we make S n and S p equal to 0. So, when you put these conditions into the previous equations the detailed equations that we showed earlier, then we get this delta p n as this and delta n p as this. So, you can see that there is a bias dependence plus there is some exponential dependence depending upon the junction depend which depends upon the w n, w p and the position at which you want to take the current.

This gives you from these you can work out what is J n at minus w p and J p at w n, because we are diffusive currents. So, you just have to plug this in so basically the current is nothing but minus or minus plus or minus q D d n slash p divided by d x, so depending upon whether you have positive and negative you just work out the current by differentiating this, and you will get these expressions ok.

So, when you get these expressions, these are similar to what to get for a P-N junction in dark. So, J n at minus w p is nothing but q N i square D n divided by N A L n into exponential q V a q V by k T minus 1, the same similar expression except that you have p replaced by n and A replaced by D, you get for J p. And if you sum these together, you will get the same current as you get in P-N junction in dark. So, this is the dark current in P-N junction, which is as a result of diffusion all right.

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$$\text{Hence } J_{diff} = J_n(-w_p) + J_p(w_n) = J^o_{diff}\left(e^{qV/kT} - 1\right)$$

$$\text{where } J^o_{diff} = qn_i^2\left(\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p}\right)$$

Now, so hence we can say that J diff is equal J n at minus w n, J n at minus w p plus J p at w n, which is equal to J naught diffusion into exponential q v by k T minus 1 and J naught is this. So, this is what we expected from diffusion current.

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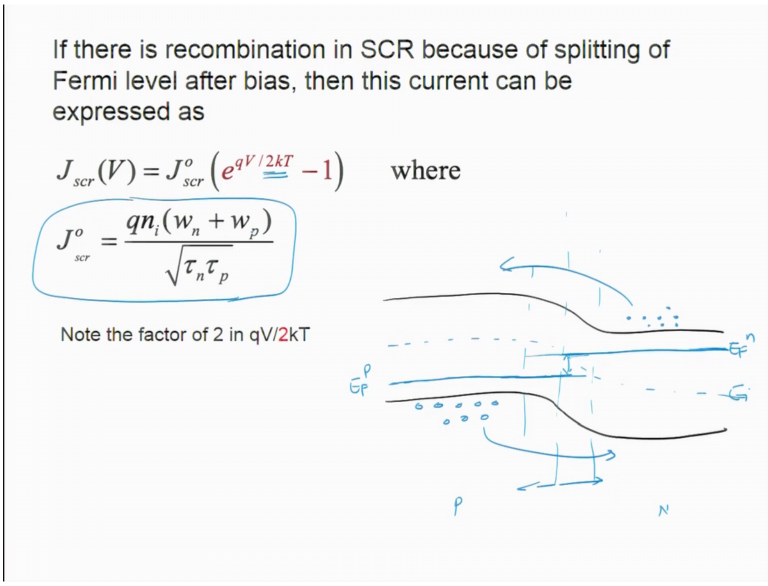

But, what happens in solar cells is that, we although we were assuming earlier that there is no recombination current in space charge region, there is a recombination current in space charge region, because the Fermi levels are now split ok. When the Fermi levels, I split, so because your semiconductor is like this your so this is your P-N junction right.

So, this is p-side, this is n-side, if I take it for electrons, the Fermi levels will go in this fashion, and holes Fermi level will go in this fashion and there is a split in the Fermi level. So, the intrinsic Fermi level goes like this, but within this region also. Since, you have Fermi levels going across like this, you have a split in the Fermi level within that. So, remember this is a junction right. So, within this also you have a change in the since the Fermi levels are now, so these Fermi levels you have a Fermi level for so this is E F, we can say p. This is E F n and because of this is split of Fermi level within these space charge region you have, because remember this is also p-type right.

Although it is a depletion region, it is a P-type semiconductor, and this is N-type semiconductor. And the and these Fermi levels are also so what we are showing here is the splitting of the continuity of E i, but E i is irrelevant right. So, it will so you will have this E F p continuing in some manner E F n continuing in certain manner. So, then exact nature we cannot depict here very clearly, but you are going to have certain split of Fermi level because of light bias.

Now, if you have certain split of Fermi level applied bias and the fact that you have you have electrons migrating from one side to another and holes migrating one side to another. There is always a possibility of recombination within this region ok. So, when you have electrons going from here to here, holes going from here to here, the recombination there is certain amount of recombination in the space charge region. And this space charge region recombination gives rise to what we call as a space charge current, which we ignored in the P-N junction in dark analysis earlier.

So, in the context of solar cells and practical devices, we do have to consider this. And it turns out that this current actually has a dependence of exponential of q V by 2 k T instead of exponential of q V by k T. So, this is sort of non-ideality in the P-N junction diode that we observed all right. So, when you for example, if you take the if you just plot it as a function of log of current versus voltage, the slope should be equal to q by k T right, but what we get is the slope is equal to q by 2 k T for non-ideal diode, often the mixture is often the behaviour is mixed.

And this is the current which is the space charge current pre-exponential factor, which is q n i into w n plus w p divided by square root of tau n tau p. And this is from the same current that same SCR current that we got so this is the SCR current that we invoked, when we set key in that now you have P-N junction which has effect of both the P-N junction, which has a SCR in which recombination and generation is the possibility ok, earlier we ignored this in our P-N junction analysis.

So, now if we do not ignore this, then we have to consider this space charge region current. So, within that expression that we looked at the last lecture, if we made the illumination term 0, then only the recombination term remains. And the recombination term that remains gives you this space charge current, which is essentially we can say dark recombination current all right. And this has a factor of q V by 2 k T. So, in addition to dark current that you have here there is extra dark current which is here which has a factor of q V by 2 k T, which is because of space charge recombination which was ignored earlier.

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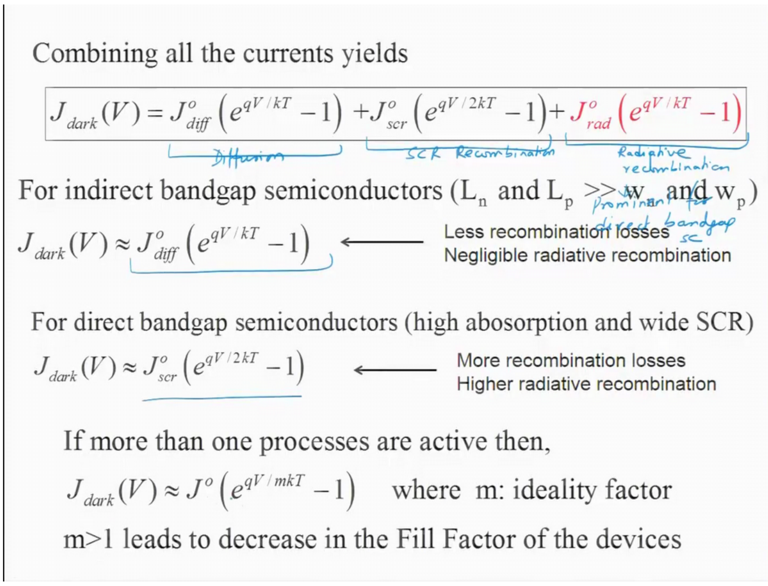

So, if you combine all the two things are together, so J dark has a diffusive component this is the diffusive component, this is the space charge component and there is another component that we have added here, which is because of radiative recombination, which will always occur ok. Radiative recombination is present in all the semiconductors, as a result specially in the direct semi band gap semiconductor radiative recombination is very prominent.

So, another term which is added ad hoc, whose dependence goes as q V by k T minus 1. So, there are three components of dark current. One is the diffusion current, another is the space charge current, third is the so this is for diffusion that we that we took for similar P-N junction analysis, this is space charge recombination, and this is space charge region recombination. And this is radiative recombination, which will always be present in a semiconductor, whose extent will be determined by whether it is a direct band gap semiconductor or indirect band gap. So, this term is prominent in prominent for direct band gap semiconductors ok.

So, for indirect band gapped semiconductors generally L n and L p are much larger than w n and w p. And as a result the that so for indirect semiconductor like silicon, the dark current is generally so when the diffusion distances of carriers are longer, which means they can be alive for longer distances. As a result they do not recombine too much in space charge region.

And even the radiative recombination is and radiative recombination is smaller in that band gap semiconductors anyway, because you do not you have to have a phonon assistance there, and that does not make the that does not enable the recombination very easily. So, these two term are not so prominent for indirect gap band gap semiconductors, which have longer hole and electron minority carrier lifetimes as a result longer diffusion lengths.

So, in this case only the diffusion length, diffusion related dark current persists. So, you will see in the dark data the dependence will be q V by k T for the so there are less recombination losses. And negligible radiative recombination for a indirect band gap semiconductor provided your diffusion distance is a large.

However, for direct band gap semiconductors, which have high absorption and wide space charge region. They generally have very wide space charge region. These materials generally have a dark current which has q V by 2 k T dependence. So, this space charge recombination is higher in these materials, especially when you have direct band gap semiconductors, but generally it is not always very ideal.

So, if you have more than one processes active, then we generally say that J dark is equal to J naught into exponential divided by exponential of q V divided by m k T minus 1, where m is the ideality factor So, we say if m is greater than 1, then obviously it leads non-ideal diode and that reduces the fill factor of the device as well, because of increased recombination ok. So, basically you can say that increase in this m factor of more than 1, often leads to more recombination losses as a result less current and less photocurrent that you get and less fill factor of the devices.

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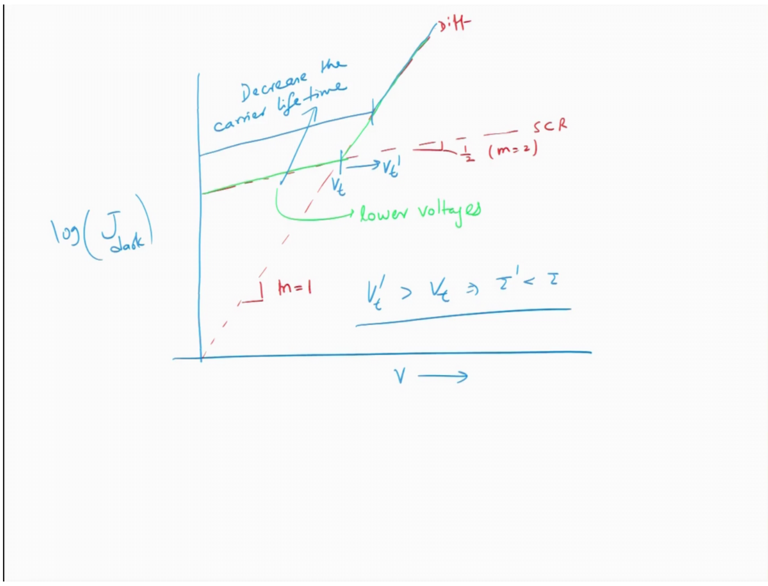

So, if I know a plot, let us say J dark, this is at log scale as a function of V ok. So, if I draw only for diffusion current, then for diffusion current the slope should be like this right. This is for diffusion current which has the slope of 1 or for which m is equal to 1 right. And if you have a space charge current, that space charge current will so this is diffusion and this is space charge assisted.

In this case, the slope is equal to half right, because in this in one case you have so in this case m will be equal to 2. Generally, what we observe is we have a trend like this, so we have in the at the smaller voltages, we have space charge recombination. When all the traps are filled, then it goes to diffusion current. This typically happens at lower voltages ok. So, at lower voltages you will have a space charge current recombination, when the slope will be half. And at higher voltages, when the all the traps are filled recombination reduces, as a result the carriers move away from the junction.

However, if you now what is the what is likely to happen, if suppose carrier lifetime decreases, if carrier lifetime decreases in that case the space charge recombination will become more and more. So, if the carrier recombination increases, this curve tends to shift to the so it will shift to up or down, it will shift in this direction.

So, if your career recombination increases, it tends to go up. So, this will go up, if you decrease the carrier lifetime. So, when the carrier lifetime reduces, then of course recombination is larger. As a result recommendation current dominates over the diffusion current ok. So, your you will obtain, so basically your dark current will also be dominated by recombination than the diffusion current.

So, this is so basically the shift that happens the shift happens at higher voltages. So, you can see that V transition V transition is higher in so V transition 1 is higher with respect to V t or prime. So, V t prime is greater than at V t, because tau prime is smaller than tau ok, this is what happens is observed in semiconductors.

Now, let us look at P-N junction in equilibrium. So, this is what you will observe in a P-N junction in a real P-N junction under dark, you will not obtain always at slope of 1. It is likely that you will obtain a slope of 1 by 2 because of recombination which we earlier ignored in our P-N junction analysis. And this is deviation from ideality, because now we are saying that there is a recombination in space charge region. Whereas, earlier assumption was that space charge region had no generation, and no recombination. So of course there is no generation, but there is recombination ok.

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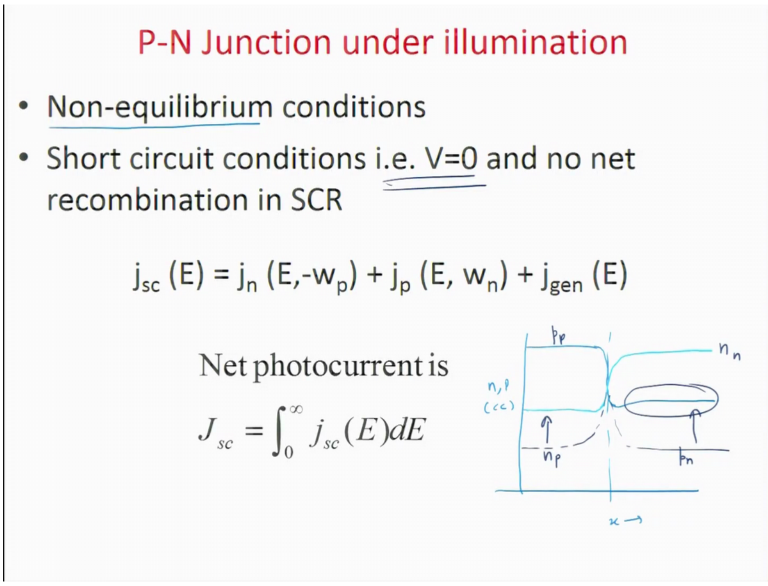

Now, let us look at this condition of a P-N junction under illumination. So, when you have P-N junction under illumination, then what we create is when we then we create conditions, which are called as non-equilibrium condition. Non-equilibrium conditions, because you suddenly flood the semiconductor with lot of carriers and energy levels move up and down.

So, Fermi levels for example, both n and p concentrations increase rapidly within the semiconductor and as a result you have huge increase in the carrier density on both sides. So, what will happen in this case is so if you plot the carrier density for example, the carrier density if you plot, suppose this is a junction so this is let us say carrier density n or p per cc. And this is distance x, you will see that on p-side, you will have large p, but you will also have you will also have large n.

Whereas, earlier n was if you plot it at equilibrium, this n would have been at very low level right somewhere like that. Similarly, on the n-side this carrier density would be very large and this would be very increased on the p-side as well. Whereas, it was in case of the device when it was in dark, this could be the behaviour. So, this would be the carrier density n and this would be so this would be n this would be n p. This would be p p, and this would be p n. So, p n increases, n p increases and of course there is a change in p p and p n as well.

So, minority carrier concentration suddenly increases a lot a lot. So, there are major energy shifts within the semiconductor. And those energy shifts within the semiconductor give rise to a large, we can say a negative current in the semiconductor. Because, remember in the in the P-N junction the forward bias, we are looking at the current which is so you have hole diffusion from p to n side and you have electron diffusion from n to p side.

So, you have a certain current sign in this case, what will happen in this case is if we now look at from the sign of current, since the sign of current generation current in this the current, which is produced at 0 bias ok. So, we are looking at the condition first at 0 bias. So, when you have 0 bias, then the current starts flowing in the opposite direction, you have large negative current which means negative current will mean you have large flow of holes from n to p side, because you have sudden increase in the hole concentration on this side.

Similarly, you have large electron current from one side to another. So, you have flow of carriers, because you can see that for electrons to go from this side to that side they still have to face a barrier right, because there is no bias there is no bias. So, if you look at the; if you look at the Fermi level, if you look at the energy situation, if I can maybe insert a slide here, I will come back to the this slide again.

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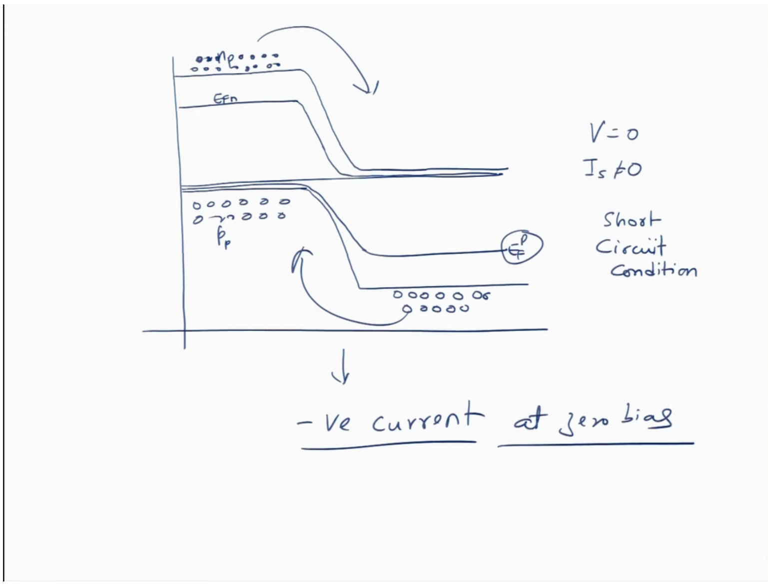

So, if I just draw energy band diagram, so let us say this is at 0 and this is your E c and this E c is like this and this is ok. So, we are having V is equal to 0, but I s is not equal to 0. So, this condition is called as short circuit condition all right within so in this short circuit condition, what will happen is that?

Since, you so you have of course increased the hole concentration, so hole concentration will obviously be increased. So, there is certain p p, but you also have large increase in n p, which means the quasi Fermi level that corresponds to electrons will increase here. So, this is E F n. So, if I just plot it like this, this E F n will be something like that; so, this is E F n.

Similarly, you will have quasi Fermi level for holes this is E F p, so this is Fermi level corresponding to holes from the n-side, because on this side the hole concentration also will increase ok. So, this increase in the hole concentration on p-side sorry n-side and this increase in the electron concentration on the n-side leads to a raising of Fermi level or quasi Fermi levels corresponding to electrons and holes closer to conduction and valence band.

So, now you can see that electrons from this side, if there are lot of electrons on this side, they can jump from here to here. Similarly, if there are lot of holes from this side, despite having a diffusion gradient, despite having more number of holes from this the side, there is a driving force because of splitting of Fermi levels, because Fermi level produces a inbuilt force for these holes to migrate from this.

So, electrons will come this side, holes will go this side. This is the flow of electrons and holes in the opposite direction and this contributes to what we call as negative current at zero bias. And this happens because of its splitting of Fermi levels, because the Fermi level for electrons on p-side is very high, Fermi levels for holes on n-side is very high.

And these splitting of Fermi levels provide driving force for electrons to move from p to n side contrary to popular wisdom right. You would assume normally the diffusion to take place along the diffusion gradient, but this is not diffusion gradient we can say this is the sort of potential gradient or chemical potential gradient. So, now this is in some sense it is called a uphill diffusion. And this diffusion is happening because of a gradient in the Fermi energy for electrons and gradient in the Fermi energy for holes. So, holes go from n to p side, and electrons go from p to n side.

As you increase the bias as you increase the bias, slowly and slowly more electrons will go from this side to this side holes will go from this said to that side, and they start countering this and that is what happens in the solar cells. As increase the bias, the current decreases. The current starts becoming form more negative to less negative and eventually it goes to 0, so that is what happens, so which is which means your forward current keeps increasing the bias induced current that starts checking over the over the current that is produced by chemical potential gradient, as a result of its splitting of Fermi level.

So, essentially if I go to now previous slide, we are saying that short circuit condition means V is equal to 0, there is no net recombination in space charge region. The j s c is equal to j n at minus w p plus j p at w n plus j generation current. This generation current will start dominating, and the net photo current is now equal to integration from 0 to infinity. So, you can do it from 0 to infinity although, which can do it from E g to infinity also. So, this is j s c for a spectral current, you need to integrate for all the energies ok.

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$$j_n(E,-w_p) = -\left(\frac{qI_s(1-R)\alpha L_n}{\alpha^2 L_n^{\,2}-1}\right)\times\left\{\frac{e^{-\alpha(x_p-w_p)}\left(\frac{S_nL_n}{D_n}\cosh\left(\frac{x_p-w_p}{L_n}\right)+\sinh\left(\frac{x_p-w_p}{L_n}\right)\right)-\left(\frac{S_nL_n}{D_n}+\alpha L_n\right)}{\frac{S_nL_n}{D_n}\sinh\left(\frac{x_p-w_p}{L_n}\right)+\cosh\left(\frac{x_p-w_p}{L_n}\right)}+\alpha L_n e^{-\alpha(x_p-w_p)}\right\}$$

$$j_p(E,w_n) = -\left(\frac{qI_s(1-R)\alpha L_p}{\alpha^2 L_p^{\,2}-1}\right)e^{-\alpha(x_p+w_n)}\times\left\{\frac{\left(\frac{S_pL_p}{D_p}\cosh\left(\frac{x_n-w_n}{L_p}\right)+\sinh\left(\frac{x_n-w_n}{L_p}\right)\right)-\left(\left(\frac{S_pL_p}{D_p}-\alpha L_p\right)e^{-\alpha(x_n-w_n)}\right)}{\frac{S_pL_p}{D_p}\sinh\left(\frac{x_n-w_n}{L_p}\right)+\cosh\left(\frac{x_n-w_n}{L_p}\right)}-\alpha L_p\right\}$$

$$\eta_{QE} = \frac{-j_n(E,-w_p) - j_p(E, w_n) - j_{gen}(E)}{qI_s(E)}$$

So, we will look at these expressions in the next lecture, because we are running out of time. So, essentially the purpose was to show, how you get large photo current which is negative in sign, when you have zero bias and illumination on, we will dwell on this further looking at these expressions which are in front of you in the next lecture ok.

Thank you.