Solar Photovoltaics: Principles, Technologies and Materials

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Lecture – 24

P-N Junction Analysis (Light)

So, welcome again to this new lecture on Solar Photovoltaics Principles, Technologies and Materials. So, we will again look at the P-N junction in light. So, let me just recap the last lecture in the last lecture we were talking about P N junction.

So, we in the lecture before we did analysis of P N junction in light and we got the current expressions for electron current, whole current and the space charge region current. And we looked at the simplifying those equations with making certain assumptions. So, first assumption was that what will happen if you make if you analyse them for P N junction in dark and without illumination and that is straight forward; it should take you to P N junction in equilibrium which means there is no current flowing.

And then we looked at the case of P N junction in dark without illumination, but with applied bias and then that should take us back to the P N junction in dark without the bias. However, later we introduced since we introduced space charge region current which is which is finite in practical diodes. And as a result of this recombination within space charge region as well as radiative recombination in the semiconductors we have a recombination current from space charge region and this gives rise to non ideality in the a devices. So, if you recall we had this curve we had this expression here.

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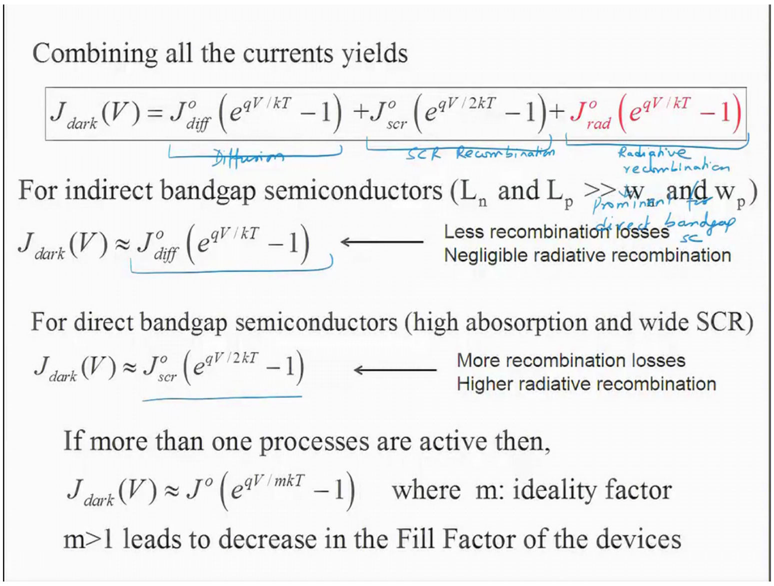

Combining all the currents yields

$$\boxed{J_{dark}(V) = \underbrace{J^{o}_{diff}\left(e^{qV/kT}-1\right)}_{\text{Diffusion}} + \underbrace{J^{o}_{scr}\left(e^{qV/2kT}-1\right)}_{\text{SCR Recombination}} + \underbrace{J^{o}_{rad}\left(e^{qV/kT}-1\right)}_{\text{Radiative recombination}}}$$

Prominent for direct bandgap sc

For indirect bandgap semiconductors (L_n and $L_p >> w_n$ and w_p)

$$J_{dark}(V) \approx \underbrace{J^{o}_{diff}\left(e^{qV/kT}-1\right)} \longleftarrow$$

Less recombination losses
Negligible radiative recombination

For direct bandgap semiconductors (high abosorption and wide SCR)

$$J_{dark}(V) \approx \underbrace{J^{o}_{scr}\left(e^{qV/2kT}-1\right)} \longleftarrow$$

More recombination losses
Higher radiative recombination

If more than one processes are active then,

$J_{dark}(V) \approx J^{o}\left(e^{qV/mkT}-1\right)$ where m: ideality factor

m>1 leads to decrease in the Fill Factor of the devices

This tells us that dark current is equal to the diffusion current which we also derived earlier. But in addition now we have added space charge recombination generated current and radiative recombination.

And these factors are dominant in practical devices. So, if you have indirect bandgap semiconductor; generally it is observed that radiative recombination is higher and space charge recombination is lower as a result sorry indirect bandgap semiconductor because you have lesser in radiative recombination. And if the diffusion lengths are larger than the junction widths then as a result a space charge region width, then your dark current is predominantly diffusion limited.

However, for direct band gap semiconductor which have high absorption wide space charge region; as a result the carriers do recombine. So, more recombination losses and high radiative recombination in these semiconductors; this gives rise to a dependence of q V by 2 k T which is observed. And generally what happens is that we see more than one processes as a result we have a; the generalize this equation as J dark V is equal to J naught into exponential q V by m k T minus 1 where m is the ideality factor. So, when m is equal to 1 which means the behaviour of device is ideal, but if m is greater than 1; then the device behaviour is non ideal which means more than one processes are active in terms of dark as far as dark current is concerned.

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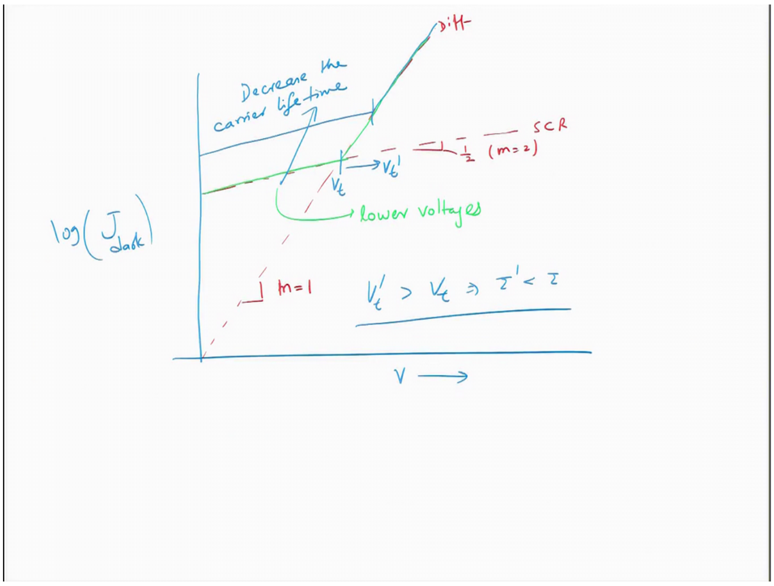

So, this is what we were doing. So, generally there is a transition from space charge current to diffusion current that happens in very low voltages. But if your carrier life times are smaller careers diffuse they combine or diffusion lengths are shorter, then the transition to diffusion current is at higher voltages that is what we saw.

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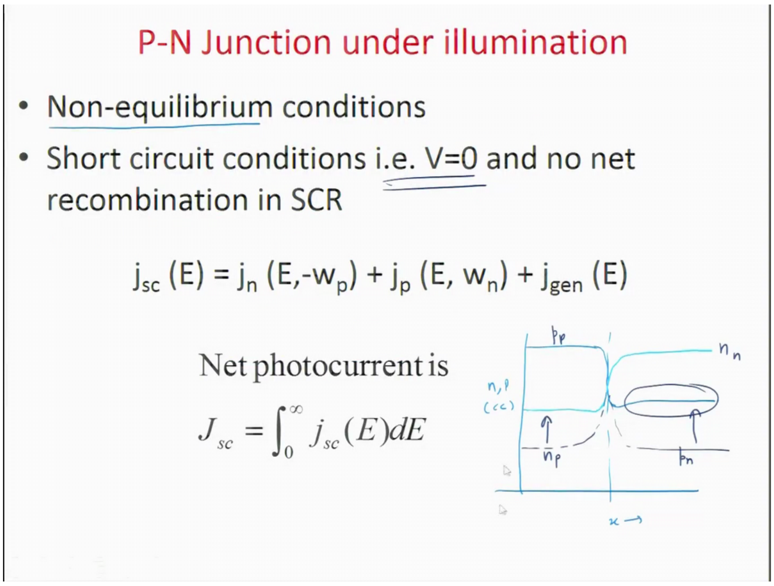

P-N Junction under illumination

- Non-equilibrium conditions
- Short circuit conditions i.e. V=0 and no net recombination in SCR

$$j_{sc}(E) = j_n(E,-w_p) + j_p(E, w_n) + j_{gen}(E)$$

Net photocurrent is

$$J_{sc} = \int_0^\infty j_{sc}(E)dE$$

And then finally, we were looking at the P N junction under illumination; where we said that you have a semiconductor device with 0 voltage applied. And there is no net recombination S space charge region; however, you have lot of generation. So, as a result you have large generation current within the space charge region at um at 0 bias.

So, the total current is now equal to electron current at minus w p plus whole current at plus w n plus the generation current um. You will have some recombination also, but the generation current dominates over anything else as a result. So, you will have already radiative recombination in the device, but since you do not have any applied bias ah; there is no space charge related current here SCR current.

So, this total current is the integration of this space spectral current over the whole energy range. What happens here is the quasi Fermi levels for electrons and holes because of increase in population of electrons in the p side and holes on the n side the Fermi levels are split.

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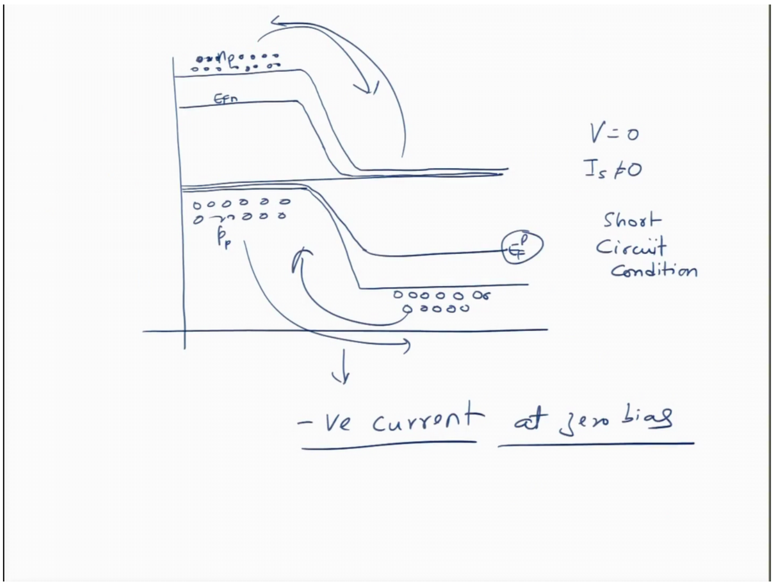

And this change in the Fermi levels on p and n side gives rise to migration of hole from entropy side and p to n side electrons from p to n side which is counterintuitive against the P N junction in dark. And this gives rise to a current which is negative in sign and that is what you observed at 0 bias. And this is the current which is given by split changes in the Fermi level and this Fermi level gradient is the one which drives the electron down to down to the ; n side from p side and hole from n side to p side which is normally not the case in P N junction in dark. So, now we are going to further analyse this.

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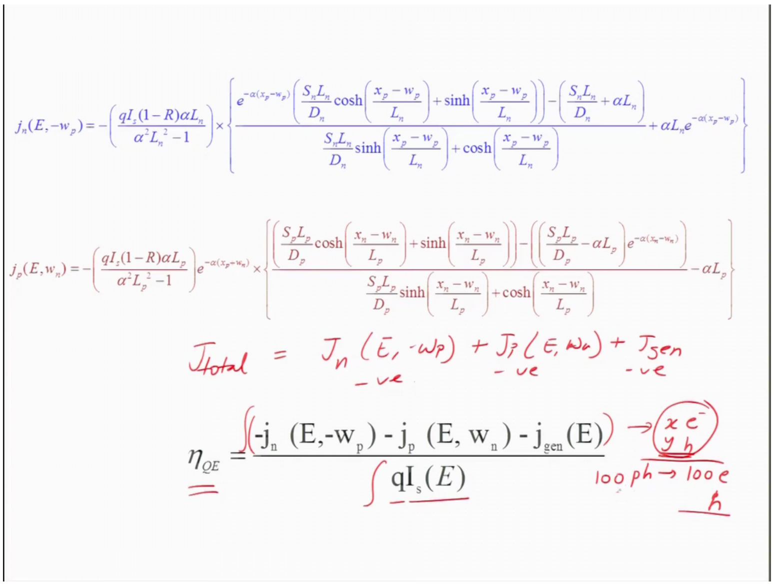

$$j_n(E,-w_p) = -\left(\frac{qI_s(1-R)\alpha L_n}{\alpha^2 L_n^2 - 1}\right) \times \left\{ \frac{e^{-\alpha(x_p-w_p)}\left(\frac{S_n L_n}{D_n}\cosh\left(\frac{x_p-w_p}{L_n}\right)+\sinh\left(\frac{x_p-w_p}{L_n}\right)\right)-\left(\frac{S_n L_n}{D_n}+\alpha L_n\right)}{\frac{S_n L_n}{D_n}\sinh\left(\frac{x_p-w_p}{L_n}\right)+\cosh\left(\frac{x_p-w_p}{L_n}\right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

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

$$J_{total} = \underset{-ve}{J_n(E,-w_p)} + \underset{-ve}{J_p(E,w_n)} + \underset{-ve}{J_{gen}}$$

$$\underline{\underline{\eta_{QE}}} = \frac{\int\left(-j_n(E,-w_p) - j_p(E,w_n) - j_{gen}(E)\right)}{\int \underline{qI_s(E)}} \rightarrow \boxed{\begin{matrix} x\,e^- \\ y\,h \end{matrix}}$$

$$\frac{\quad}{100\,ph \rightarrow \frac{100\,e}{h}}$$

So, if you look at the further; if you just look at those equations. So, the equations in this case the j n and j p equations; you can see the current sign is in negative you have this i s term and there are other factors which are the with respect to your surface recombination velocity diffusion lengths and coefficient of thermal coefficient of absorption etcetera.

And the total current now since we said total current is negative right we said that this all these 3 currents that we look. So, we said that J total was equal to J n E minus W p plus J p E W n plus J gen; all these 3 currents are negative. So, the total current of this device is basically the current is negative.

So, minus of j n E minus w p plus minus of j p; E w n and so if you want to just convert if you need to basically integrate this and over the whole energy range and this should also be integrate over the whole energy range. And the total current which is obtained because of the current which is because of electron; hole migration and generation current this should be; so, diffusion current plus generation current this should give you the ratio of this current with respect to whatever power is incident according to that. So, number of basically this is a spectral flux or spectral energy.

So, if multiply this by charge you will get thus that many number of carriers that should be created. So, ratio of these two will give you the quantum efficiency of the device ok. So, suppose you had 100 photons falling here 100 photons will give you 100 electrons plus 100 holes right. What you get here will be some other number; it will be x electrons and some y holes let us say right because of differences electron hole current they are not similar. So, the ratio of current corresponding to this; this with respect to what should have been ideally created is the quantum efficiency ok. So, this is what you got and this is what you should get ideally.

And of course this number x and y is always going to be smaller than; so sum of this is always going to be smaller than 100 that you can here. So, that is why the quantum efficiency are not 100 percent, but; however, lower; so even here quantum or that of 80 percent, 70 percent and so in semiconductor devices.

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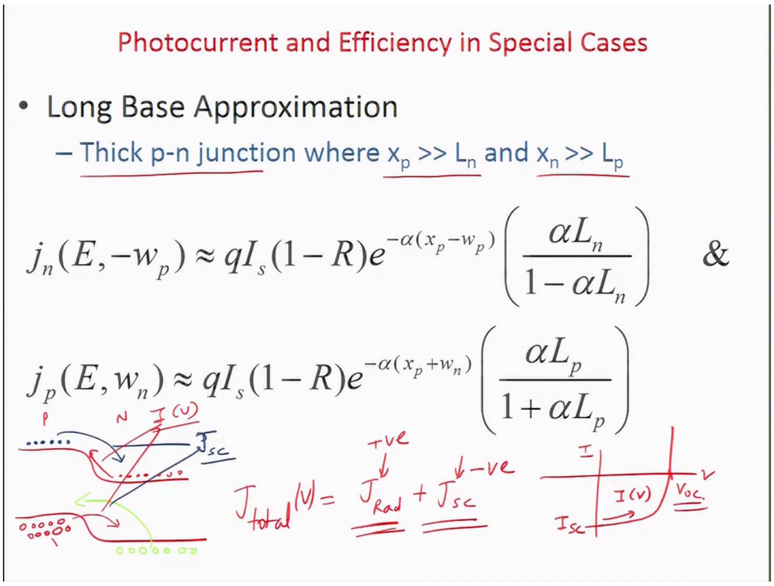

Photocurrent and Efficiency in Special Cases

- Long Base Approximation
  - Thick p-n junction where $x_p >> L_n$ and $x_n >> L_p$

$$j_n(E,-w_p) \approx qI_s(1-R)e^{-\alpha(x_p-w_p)}\left(\frac{\alpha L_n}{1-\alpha L_n}\right) \quad \&$$

$$j_p(E,w_n) \approx qI_s(1-R)e^{-\alpha(x_p+w_n)}\left(\frac{\alpha L_p}{1+\alpha L_p}\right)$$

So, to solve this further you can you can approximate and this approximation is um; first you can make a long base approximation long base approximation means that diode is very thick, the thin in the p-n junction is extremely thick and we assume that x p is greater than x L n and x n is greater than L p.

In such a case surface recombination term becomes invalid as a result you can modify these expressions as the electron and hole kind expressions are modified in this fashion. So, you can see here that the surface recombination terms vanish. So, these two terms become much more simpler primarily dependent upon the a minor carrier life times absorption coefficient and the width of junction and width of device that is the only factor it depends upon.

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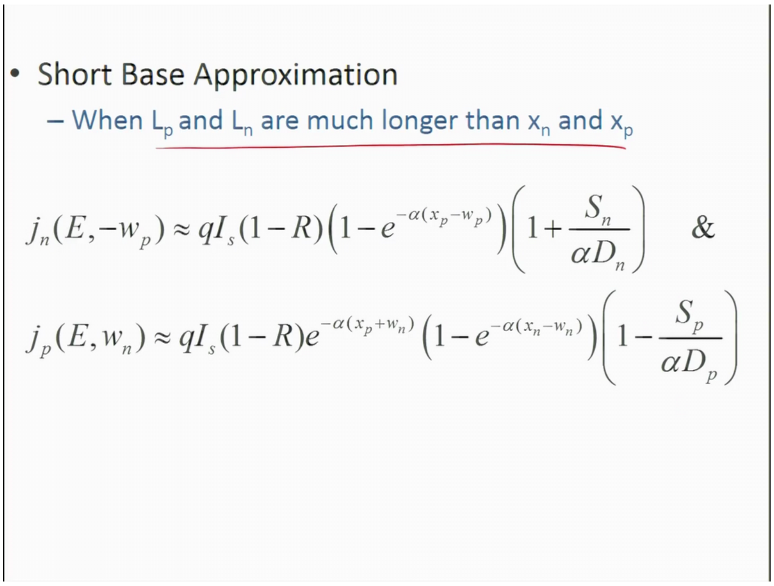

- Short Base Approximation
  - When L_p and L_n are much longer than x_n and x_p

$$j_n(E,-w_p) \approx qI_s(1-R)\left(1-e^{-\alpha(x_p-w_p)}\right)\left(1+\frac{S_n}{\alpha D_n}\right) \quad \&$$

$$j_p(E,w_n) \approx qI_s(1-R)e^{-\alpha(x_p+w_n)}\left(1-e^{-\alpha(x_n-w_n)}\right)\left(1-\frac{S_p}{\alpha D_p}\right)$$

You can also make short base approximation when L p and L n are much longer than x x n and x p. So, you can see that this is the assumption that we make this is the short base diode; in such a situation your surface recombination is is relevant, but L n and L p becomes irrelevant.

Because they are longer than S n and S p; as a result you will see that L n and L p disappear what you have a surface recombination term appearing. So, this is how you simplify the equations that you see in the first slide; I mean this has both the terms the recombination term; the surface recombination term as well as the diffusion length term. So, we make these approximations to calculate these currents with much more simpler. So, this is what the current you will get for without the bias. So, of course, the total current that you will obtain is J total that you will have is. So, minus J s c is the one which you obtained from the short circuit and whatever is J Rad which is the positive current which is going to give rise to.

So, so this or you can I mean plus and minus sign will depend upon how you take , but this is the let us say if you make it this plus this will be the negative current, this will be the positive current radiative current. And this radiative current or recombination current or diffusion current whatever you generate as a function of bias when you apply bias this will start countering this current.

So, that is why you will see what you get at 0 bias if you plot I V; this is the short circuit current all right, at 0 bias. And as you keep applying bias; the curve goes like this means your I S C is being now counted by I V; which is the diffusion current which is the space charge recombination current. And if you have any radiative recombination current that should also contribute in they are all positive currents.

So, all the positive current factors which we saw earlier for P N junction in dark; they will start opposing this negative contribution. So, and that is obvious from the Fermi level and that that is obvious from the; this diagram as well. So, this is the P N junction diagram. So, the negative current is because of; so this is p, this is a n. So, negative current is because of movement of let us say so we said that movement of holes from oops from this side to that side similarly electrons will move from; so, these are the electrons.

So, both of these will give rise to J S C and as you apply bias what will happen is that; as you apply bias the holes from this side which are plenty in number. So, holes from this side they will start moving to this side and electrons from this side; so these two will contribute to I V and they will start countering your I S C ok; is that clear? So, this is what the basically reason behind the shape of the I V curve that you get why does the current become 0 at certain point? So, at certain point which is called as open circuit voltage the current becomes equal to 0 because I V starts dominating over I S C ok. So, this is what we have discussed so far.

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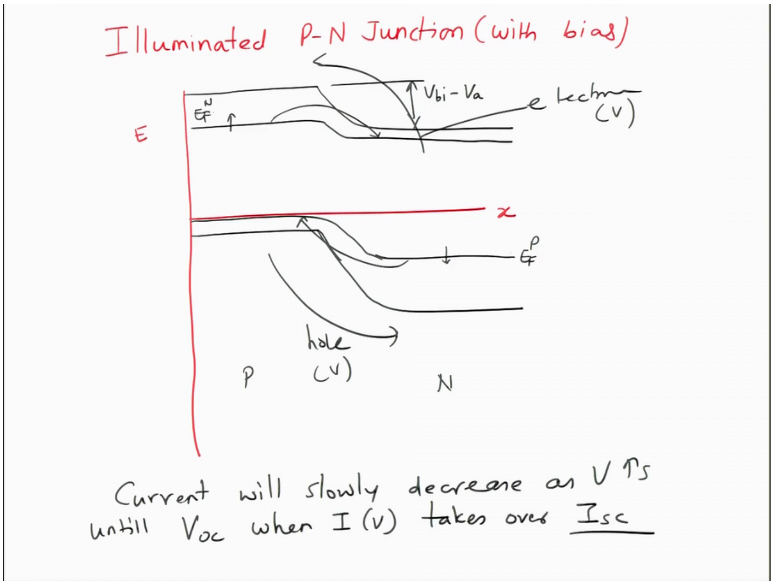

Illuminated P-N Junction (with bias)

Current will slowly decrease as V ↑s untill V_{oc} when I (v) takes over I_{sc}

So, essentially if you have now if you have a P N junction; illuminated P N junction with bias let us say so if you have. So, if you have illuminated P N junction with bias; let us say you make a plot of energy as a function of distance x. So, let us say this is your e c and this is your; so, some where here let us say ok.

This is your and this is basically you can say this is now equal to V b i minus V because now you have applied bias V a ok. So, the Fermi levels will start slowly start shifting down. So, this Fermi level which is E F N the quasi Fermi level for electrons which goes like this the quasi Fermi level for holes which is on this side; it goes like this something like that; so, this is let us say E F P.

So, normally see the beauty of this is normally you consider for P side; the Fermi level corresponding to holes because P side is a hole rich. You consider a Fermi level for electrons because this side is electron rich, but since because of illumination you have caused sudden flux of carriers; these Fermi levels are also corresponding to electrons and corresponding to holes are very high.

And that is what drives down the electron migration and hole migration from this to this side. This is now countered by electron migration from hole migration electron migration from ah; so this is from n side. So, this is electron migration and this would be hole as a function of voltage and this is what we will give rise to your decrease in the current.

So, current will slowly decrease as V increases until V o c when I V takes over I S C ok; so, that is what will happen. So, when the bias induced current which is the forward current takes over the diffusion current and space chart current and so on and so forth when it takes over the short circuit current that is generated only because of primarily because of generation ok.

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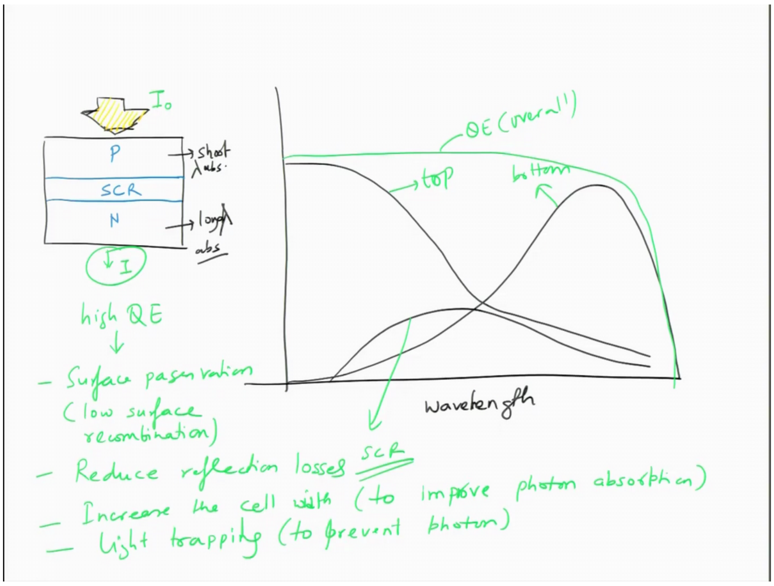

high QE

- Surface passivation (low surface recombination)
- Reduce reflection losses
- Increase the cell width (to improve photon absorption)
- Light trapping (to prevent photon)

So, generally what happens in the solar cell device is; so solar cell device let us say we have a junction like this assuming that you have junction in this fashion. So, that your sun sunlight is coming in this fashion from top; so make it orange this is sunlight and you have P N junction which is something like this. So, you have a let us say this is P side, this is N side, this is space charge region in between.

So, first you are going to have absorption in the P layer, then you are going to absorption in the N layer; in between you are going to absorption in the space charge layer. So, the quantum efficiency is varies something like that in semiconductors devices. So, if you now plot the quantum efficiency as a function of wavelength; then you are basically in the in the P layer; so shorter wave. So, you will see that the long your shorter wavelength are going to absorbed in this region.

So, in this region you will have short lambda absorption; in this layer you will have long lambda absorption. So, you will see that the absorption, the quantum efficiency for bottom layer is high in this region; the top layer contributes in this region somewhere

here something like that and if space charge region will contribute somewhere in between ok. And the overall quantum efficiency will be if I now moved on to over all this will be over all quantum efficiency.

So, this is Q E over all this is from top, this is from bottom and this is from space charge region. So, it is a space charge region is very narrow the quantum efficiency of this region is also and also if there is lot of recombination is space charge region as a result. And the quantum efficiency is smaller in case of space charge region, but generally P and N sides have high quantum efficiencies.

And high quantum efficiency is generally are obtained when; so high quantum efficiency is obtained when you have surface passivation which means you have low surface recombination right ; this is mainly due to dangling bonds. So, if you reduce the number of dangling bonds on the surface the carriers will not get recombine at the surface.

So, and also reduce the reflection losses which means the carriers are not; the photons on that reflected all of them are absorbed and then of course, increase the cell width. So, suppose you have I naught here you do not want anything to come out here. So, cell if the cell width is larger; then more radiation is absorbed in the solar cell.

So, you can put reflector for other; so, it is not a problem in silicon solar cell, but it could be a issue in the thin from solar cell where the thickness is a lower. So, so basically increase the cell width to improve photon absorption and more photons you absorb, better the quantum efficiency. And then of course, you have light trapping to prevent light loss to prevent photon loss.

So, essentially the idea is suppose you throw 100 photons on top; the idea is to maximize all of those photons in carrier generation and then carrier collection ok. So, if you throw 100 photons and you are likely to create 100 electrons in whole spheres. And device engineers job and materials engineers job is to collect all those 100 electrons and 100 holes and at the terminals so, that you collect all the carriers. Otherwise there will be recombination of carriers or if you lose photons of course, you are not going to correct you not go.

So, you want to achieve every you want to adopt every means to maximize the quantum efficiency such as by doing surface passivation. So, that it does not; so even if you absorb let us say 100 photons a carriers are going to be recombine at the surface. So, you want to passive at the surface to prevent that, you want to reduce the reflections also so that you capture all the photons. Increase the cell width, so again you capture all the photons as much as possible and then you do like trapping strategies to prevent the photos from escaping ok.

So, there are the techniques that we generally follow as far as methods of a (Refer Time: 20:58) improvements are concerned. So, and there are other factors also which you can consider to improve the current collection.

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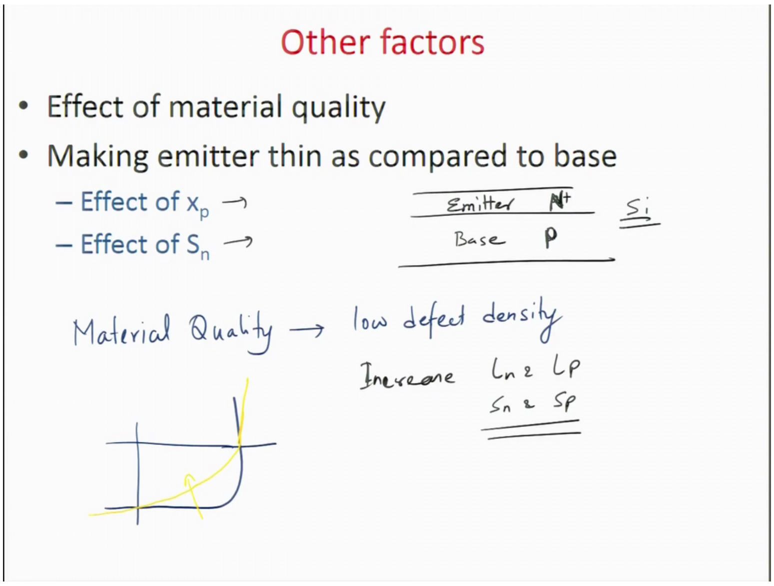

Other factors

- Effect of material quality
- Making emitter thin as compared to base
  - Effect of x_p →
  - Effect of S_n →

Emitter N^+

Base p

Si

Material Quality → low defect density

Increase L_n & L_p

S_n & S_p

And the other factors dependent upon for example, materials quality. So, material quality has various connotations to it; we will come to that. So, basically what we mean in terms of semiconductors is to materials quality means. So, material quality will mean low defect density; generally if you have higher defect density, you will have more recombination as a result more current will be; your fuel factor; basically these will reduce your fuel factor.

So, if you look at this I V curve ok; the idea is to get a I V curve which is like this, but if your I V curve happens to be like this all right; something like that. This means your I V is more dominant than it should be and remember I V is made up of what? I V is made up of your diffusion current, space charge current and radiative recombination current.

So, which means if you if you (Refer Time: 22:09) and this is well visible in the dark data and so if you analyse a dark data very well you can see which of these factors is dominating and this is most of the times related to defect density. So, if your defect density is lower than of course, your material has; so, idea is to increase L n and L p; they will improve the they will reduce the recombination and idea is also to reduce the S n and S p ok.

And of course, there are other defects in the material microstructural defection so on and so forth they should be reduced intensity. And another thing which is quite commonly talked about is in silicon context. In silicon generally the top layer is called as emitter; we will see this later on and the bottom layer is called as base. And this top player is generally P plus and this is N layer; sorry and this is this is N; this is N plus and this is P layer; I am sorry. So, this top layer is generally this is P N plus kind of junction.

So, emitter is generally made very thin as compared to base because the carrier recombination is larger in case of; so because your carrier lifetimes are longer in base electrons have longer by life times in base as a result you can make the P thicker as compared to N side. So, carriers travel longer distance as a. So, this is something; so effect of basically you can say x p and S n because you will have electrons coming on this side.

So, you are going to look at the electron recombination velocity surface recombination and a electron diffusion lengths within the P side. So, this is the their important factors as whereas, silicon semiconductor devices are concerned. So, silicon solar cells have these practices which are about making emitter thin and base thicker.

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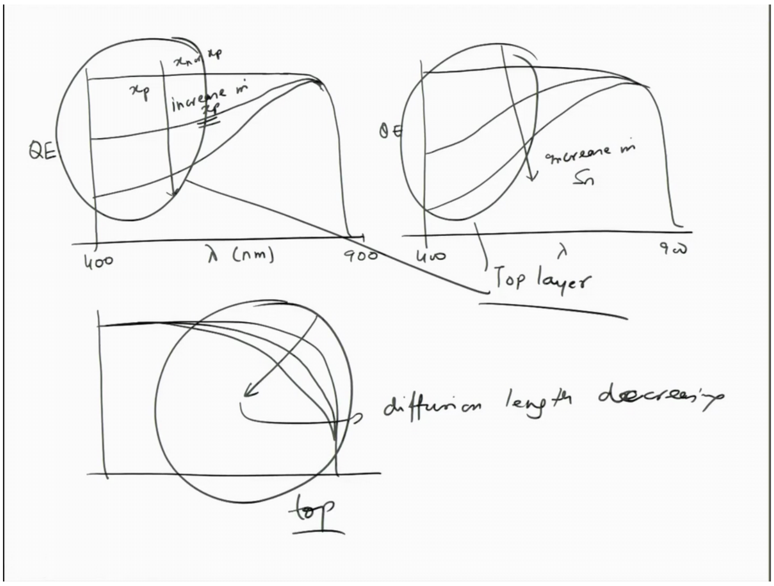

They are somethings also related to let me just show you some data with respect to. So, if you look at for example, quantum efficiency as a function of wavelength; so this is lambda in nanometre. So, we are generally plotting for a 400 to let us say about 900. So, if your x p is a thin for certain case.

So, let us say in the case where recombination is large as we increase the thickness. So, if you if you thickness is; so let us say if your x n or x p whichever you may have; if your quantum efficiency is like this and suppose you start making the layer thicker, thicker layer on one hand lead to improve the (Refer Time: 25:08) they also lead to higher recombination.

So, if you increase this x let us say x p in certain case; then increase in x p can lead to decrease in the quantum efficiency because of increased recombination. This is true for certain cases; it may not be true for all the cases, but for certain cases and then we have for example, surface recombination velocity. So, if we plot surface recombination velocity as a function of lambda. So, if you have low S n; then your curve is like this, but if your S n increases the curve tends to be like this; you can have curves like that

So, again 400 to 900 let say; so this is you can say increase in for example, S n for a certain semiconductor device and likewise, you can have effect of if this is for S n in also for S p for the other the this curve may also depending upon the. So, in this case this is the top layer because you can see that the most of the decrease is happening in the top layer this is also in the top layer. So, these are both related to top layer; it can also happen in the bottom layer like this. So, if your in this case I think it is about when your carrier recombination length you can say diffusion length decreasing ok.

So, controversies decreases and this is in the top layer region. So, whether it is because of L p or L n or S p or S n; it that will depend upon the type of semiconductor device, but you can see in which region the decrease or increase is happening. So, if the decrease is happening on the shorter wavelength side; then it is mainly because of the top layer and if it is happening in the longer wavelength side is happening because of the bottom layer. So, we will stop here today we will discuss the other things about the solar cell operation in the next class and there are few more things before we go to diffusion of materials and technologies.

Thank you.