Solar Photovoltaics: Principles, Technologies and Materials

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Lecture – 21
P-N Junction Analysis (Light)

So, welcome to this new lecture on of this course Solar Photovoltaics Principles Technologies and Materials.

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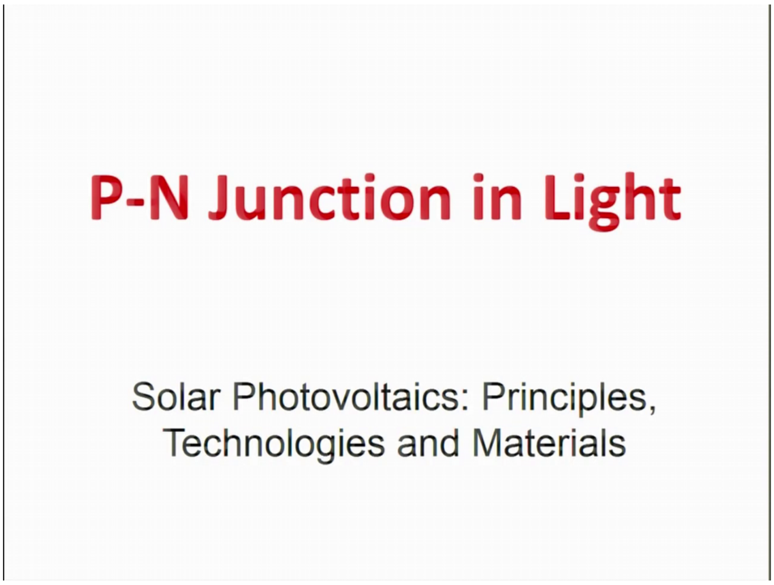

P-N Junction in Light

Solar Photovoltaics: Principles, Technologies and Materials

So, today we will learn about P-N junction light. So, before we do that let us just recap the previous lecture. So, in the previous lecture.

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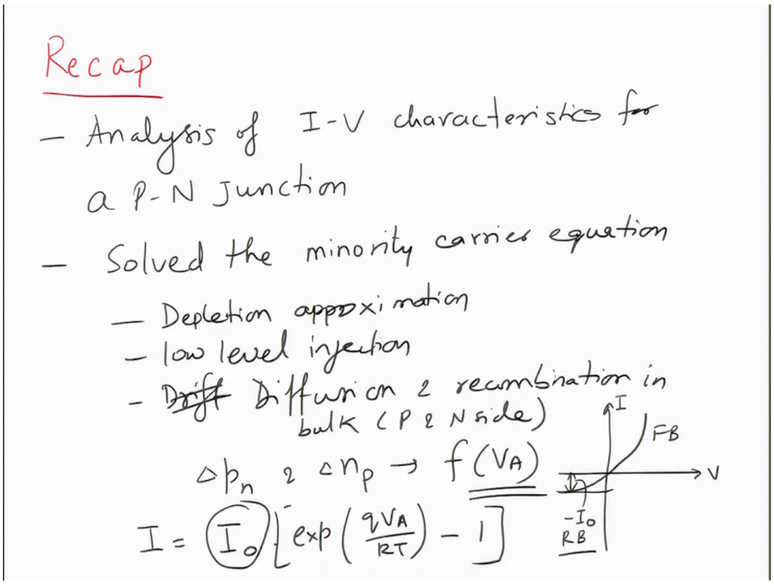

Recap

- Analysis of I-V characteristics for a P-N Junction
- Solved the minority carrier equation
  - Depletion approximation
  - low level injection
  - ~~Drift~~ Diffusion & recombination in bulk (P & N side)

Δp_n & $\Delta n_p \rightarrow \underline{\underline{f(V_A)}}$

$$I = \boxed{I_0}\left[\exp\left(\frac{qV_A}{RT}\right) - 1\right]$$

In the last class we learnt about analysis of I-V characteristics for a P-N junction and in dark and what we did was basically we solved the minority carrier equations right.

Essentially by considering depletion approximation, low level injection and we considered only drift sorry diffusion and recombination in bulk that is one P and N side all right and what we did was we first derive the expressions for delta pn and delta np. So, delta pn and would be the minority carrier that is hole on n side and delta np would be minority carrier that is electron on p side.

So, we got the expressions for these from just the junction potential analysis. So, junction potential will give you delta pn and delta np, plugin these values in the form of. So, these values, so, delta pn and delta np that you obtain are function of V A right because they are calculated in terms of junction potential.

And then you please values substitute these in the minority carrier equations which are second order differential equations. When you put them in second order differential equation and do the substitutions apply appropriate boundary conditions, that you know what happens at the boundary of depletion region and what happens at the boundary for deep inside the semiconductor. So, when you apply this boundary conditions, when you get the expressions for this current and basically you get the expression for first the delta pn and delta np and then you put that into the diffusion current expression.

So, you calculate what is jn and jp diffusion and then you some them together to calculate the total current in semiconductor device. So, what we got was something like this I is equal to I naught exponential of qVA by kT minus 1 all right and I naught is this reverse saturation current.

So, if you if you plot this I-V characteristics, the curve is something like this. So, what we have here is this is minus I naught which is in the reverse bias, this is V this is I and this is the forward current which is very large exponential function this is reverse bias ok. So, this is we did in the last class and if you go through the lectures of last class again and again, it will become more clear as you solve the diffusion equation by second order equation yourself with this simple second order differential equation which is very easy to. Now, what we will do today is, we will take we will analyze the P-N junction characteristics of a device in dark in light.

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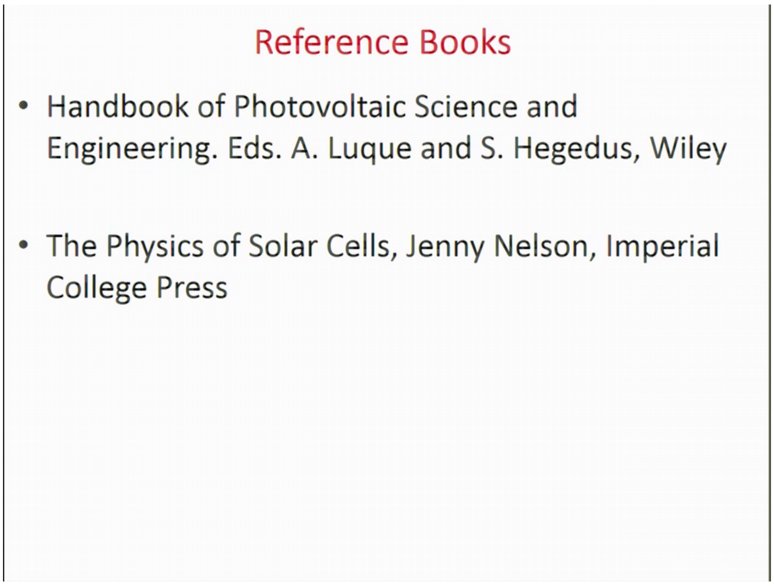

Reference Books

- Handbook of Photovoltaic Science and Engineering. Eds. A. Luque and S. Hegedus, Wiley
- The Physics of Solar Cells, Jenny Nelson, Imperial College Press

So, for this; so, I would first recommend you to these books on the reference books for this section first can be considered is this Handbook of Photovoltaic Science and Technology science and engineering by A Luque and S Hegedus Wiley publications its a very good book again it has the analysis for characteristics in light and then physics of solar cells by Jenny Nelson Imperial College Press again a good books. So, most the material that I am going to teach you going to taken from is taken from these 2 books in the context of physics solar cells, in particular this physics solar cells by jenny nelson ok.

So, now let us look at the.

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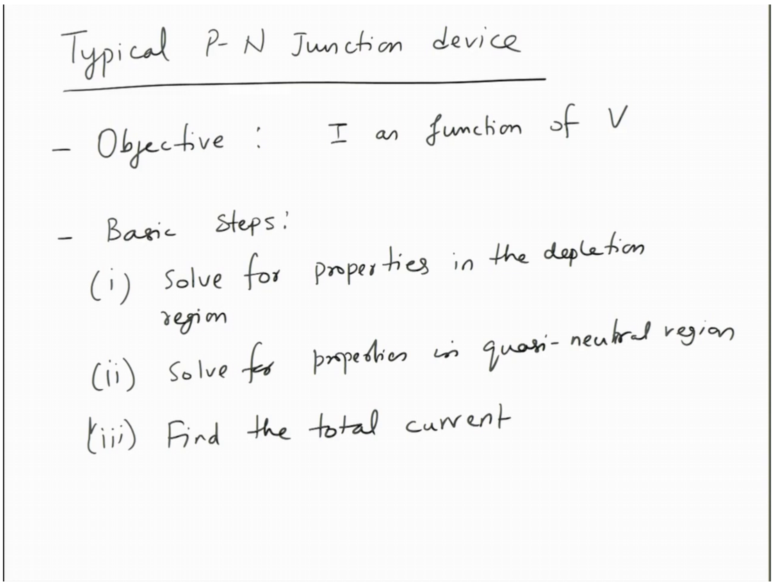

Typical P-N Junction device

- Objective : I as function of V
- Basic Steps:
  (i) Solve for properties in the depletion region
  (ii) Solve for properties in quasi-neutral region
  (iii) Find the total current

So, what we are going is that we are going to make our work for a typical P-N junction device ok. So, basically what is the objective? The objective is to determine current as a function of voltage and so, the steps that we are going to follow are basics steps are, first we solve for properties in the depletion region, then we solve for properties in quasi neutral regions, which is the bulk region ok. Because now they do not remain quasi they do not remain neutral, they become quasi neutral because you have (Refer Time: 05:52) this is light and third is find the total current all right. So, this is how we go about it. So, let us first, so, the when we do semiconductor analysis.

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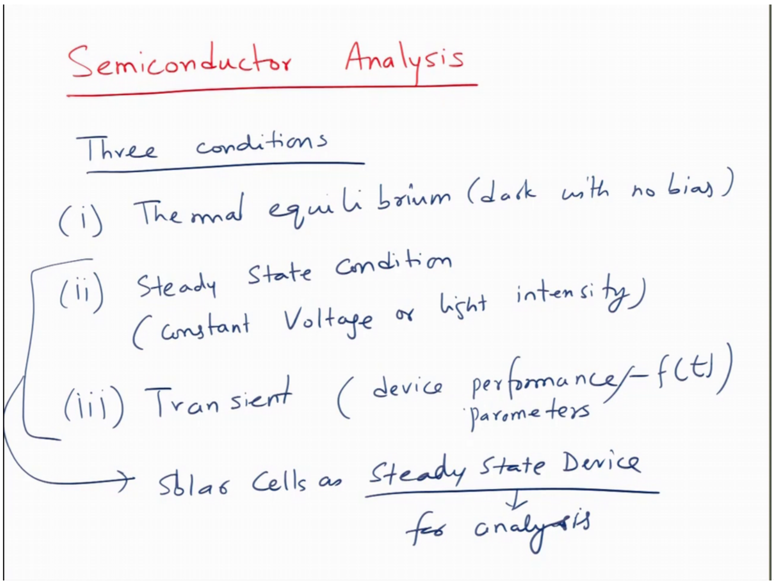

Semiconductor Analysis

Three conditions

(i) Thermal equilibrium (dark with no bias)

(ii) Steady State condition
(Constant Voltage or light intensity)

(iii) Transient (device performance/parameters – f(t))

→ Solar Cells as Steady State Device
↓
for analysis

There are three conditions that you have to follow. First condition is that you have thermal equilibrium. So, that is what we did P-N junction, that is dark with no bias that is the first condition that we followed right.

And then we have we can have. So, this is the basic condition that is present when you have no light and no bias. Then you can have another condition which is steady state condition, in which you have a constant voltage or light intensity which is applied to the device ok. And then we have third one is transient, that is device performance or device characteristics or a function of time or you can say parameters the change with time.

Generally solar cell operating these two regimes ok. So, generally solar cell obtained operator in steady state condition for in terms and conditions. So, the sake of analysis we consider solar cell as steady state device for the sake of for analysis. It makes it will simpler because if is a time dependent and become even more complex, for the sake of simplicity we the keep the solar cell device as a steady state device. That means, we consider only under a constant illumination or a constant voltage, there is no change in this parameter as a function of time.

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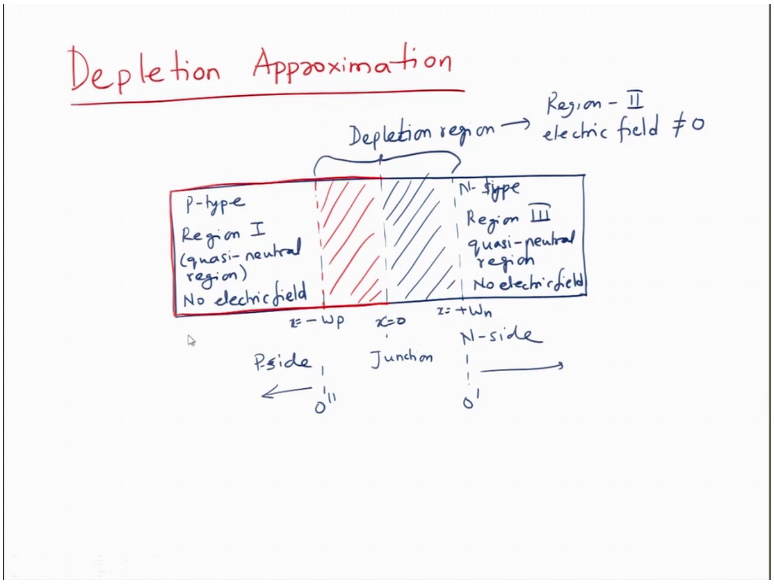

So, next we make what we called as depletion approximation, this you are familiar with already that we have made in P-N junction in dark also. So, basically we have a P-N junction this is the device, somewhere here we have a junction, on this side we have P side on this side we have N side. This is the boundary of depletion region. So, you can say this is minus w p, this is plus w n. So, this is basically you can say P type region I, which is called as quasi neutral region, which is what we called as neutral regions earlier and it has zero electric field that is no electric field which means bands remain flat ok.

This is N side, this is region III which is again you can say quasi neutral region with no electric field and then we have what we call as. So, you can say that may use a different color here. So, if let us say this was red, this P side then this boundary is the depletion region boundary on the P side and if I take the as the original color, then this is what is your. So, this total is we can says the depletion region, which is basically the marked as region II, which is with electric field. So, electric field is not equal to 0.

So, this is what we have here. So, this is at x is equal to 0 this is at x is equal to minus wp this is at x is equal to wn and you can either change the original from 0 prime, 0 double prime or you can keep the same origin just that you have to change the limits. So, what is the general procedure for solving? So, let us write the general procedure.

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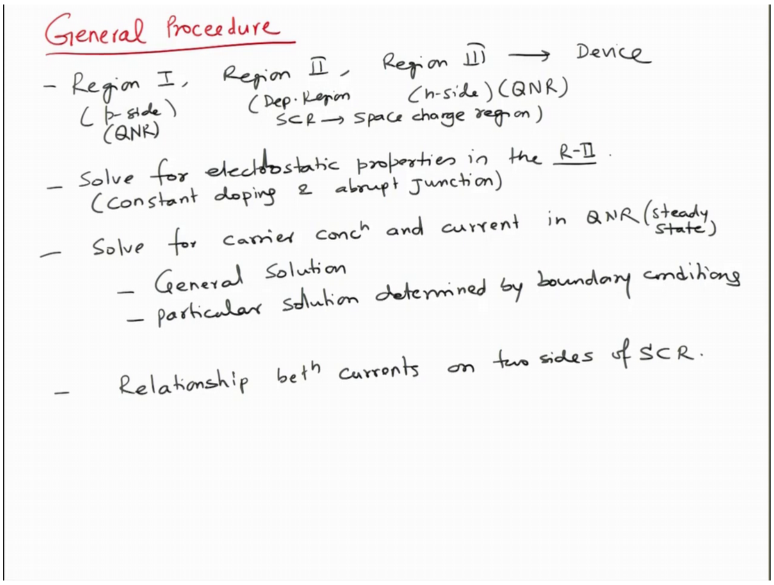

General Procedure

- Region I, Region II, Region III → Device
  (p-side) (QNR) (Dep. Region SCR → Space charge region) (n-side) (QNR)
- Solve for electrostatic properties in the R-II.
  (Constant doping & abrupt Junction)
- Solve for carrier conc^n and current in QNR (steady state)
  - General Solution
  - particular solution determined by boundary conditions
- Relationship bet^n currents on two sides of SCR.

So, general procedure is that we divide that divides into three regions region I region II and region III ok. So, this is we said its p side this is n side and this is depletion region or it is also called as SCR that is a Space Charge Region space charge region and these are called as QNR Quasi Neutral Region all right. So, you have QNR followed by SCR followed by a QNR.

And then we solve for electrostatic properties in the in region II. So, generally the solution will depend upon the doping profile, but we assume that there is a constant doping and the junction is an abrupt junction. So, we assume that its a constant doping throughout the semiconductor and abrupt junction all right.

Third is solution for solve for carrier concentration and current in QNR that is the quasi neutral region, that is region I and III under state under steady state condition. So, we assume that this is under steady state. So, and what you do in this is first you get a general solution and then you find a particular solution depending upon the conditions at the edges and boundaries of the. So, determined by boundary conditions and then we find the relationship between currents on 2 sides of SCR that is at vision region ok. So, basically depends upon how much the happen so on and so forth.

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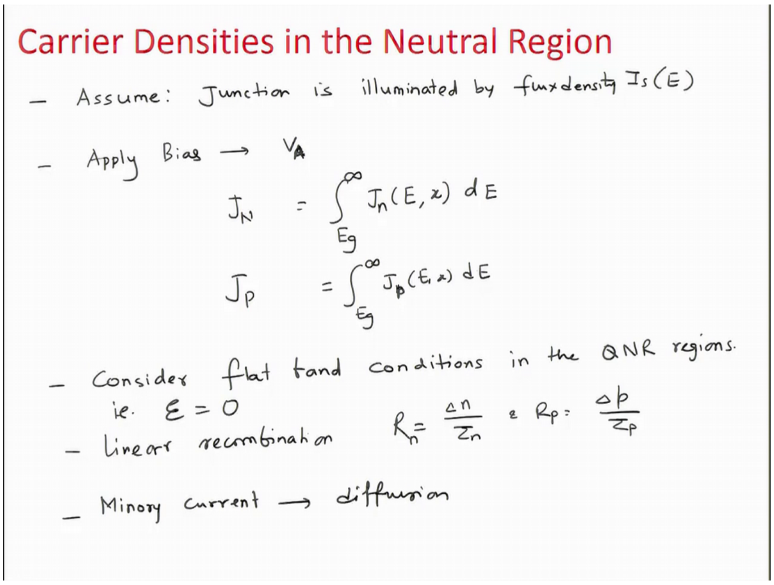

Carrier Densities in the Neutral Region

- Assume: Junction is illuminated by fluxdensity $I_s(E)$
- Apply Bias → V_A

$$J_N = \int_{E_g}^{\infty} J_n(E,x)\, dE$$

$$J_P = \int_{E_g}^{\infty} J_p(E,x)\, dE$$

- Consider flat band conditions in the QNR regions.
  ie. $\mathcal{E} = 0$
- linear recombination $R_n = \frac{\Delta n}{\tau_n}$ & $R_p = \frac{\Delta p}{\tau_p}$
- Minory current → diffusion

So, let us first write the expression for carrier densities in the neutral region. So, we consider first let us say assume that the junction is illuminated by a flux density let us say I s E of photons of energy E all right. So, when you apply bias now apply bias let us say bias is V A; V A when you apply bias you will have electronic current you will have hole current and so, electron current will be J N E will depend upon. So, when you apply with the. So, your the current will be. So, we know that absorption will occur only for radiation energies higher than the band gap energy. So, any current that you produce photocurrent as a result of illumination, will correspond to only those energies which are higher than the band gap.

So, you integrate from band gap to infinity, then we take this. So, for each energy you will have a current and then you integrate right. So, similarly J P E is Eg infinity small J n J P E x dE. So, in that sense actually this is you can say total JN and total J P for all the energies that are incident on the because you have integrated them over the interval Eg to infinity. And then we consider flat band conditions in the QNR regions right that is electric field is equal to 0 and we consider linear recombination and what does that mean? That R n is equal to delta n divided by tau n and Rp is equal to delta p divided by tau p right.

And finally, we say that minority current is mainly due to its diffusion controlled and which is what is essentially with diffusion control current which is formality carriers. So, let us anyway so.

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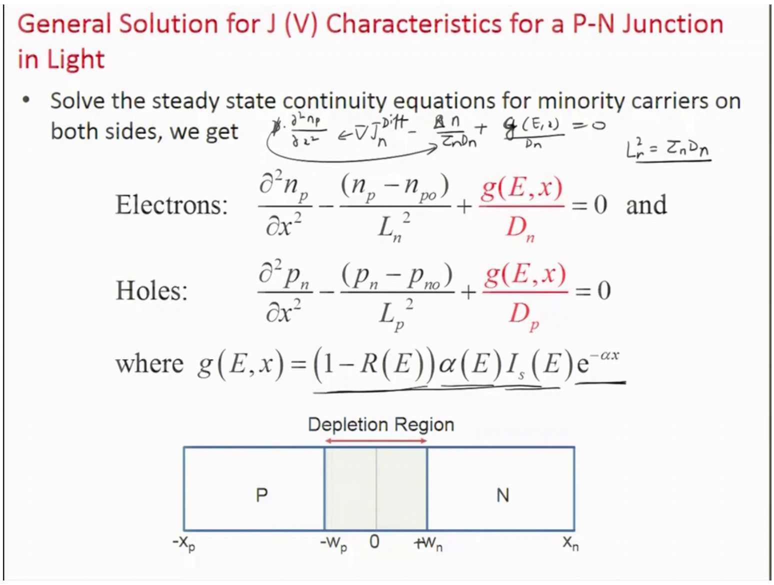

General Solution for J (V) Characteristics for a P-N Junction in Light

- Solve the steady state continuity equations for minority carriers on both sides, we get $\cancel{D}\cdot\frac{\partial^2 n_p}{\partial x^2} \leftarrow \nabla J_n^{Diff} - \frac{\Delta n}{\tau_n D_n} + \frac{g(E,x)}{D_n} = 0$ $\underline{L_n^2 = \tau_n D_n}$

Electrons: $\frac{\partial^2 n_p}{\partial x^2} - \frac{(n_p - n_{po})}{L_n^2} + \frac{g(E,x)}{D_n} = 0$ and

Holes: $\frac{\partial^2 p_n}{\partial x^2} - \frac{(p_n - p_{no})}{L_p^2} + \frac{g(E,x)}{D_p} = 0$

where $g(E,x) = \underline{(1-R(E))}\,\underline{\alpha(E)}\,\underline{I_s(E)}\,\underline{e^{-\alpha x}}$

So, we have a general solution for Jv characteristics for a P-N junction in light. So, the steady state continuity equations for minority carriers on both sides are for electrons its dell 2 np by del x 2 minus of np minus np naught divided by Ln square which is the diffusion length right. And remember we used to have d on this side which we have brought it here, because if you recall what is this equation this is basically you can say dell of J.

So, in this case we are take Jn diff right minus of R whatever the which is delta n divided by tau n and now we have taken the generation term, which is small g in this case let us a small g this is the continuity equation this was d dell 2 np divided by del x 2. So, we brought d here. So, as a result it becomes if we remove d from here it becomes dn this is divided by dn and Ln square is equal to tau n Dn right division length is equal to square root of tau n Dn.

So, for electrons we have del 2 and p by del x 2 minus of this is delta n which is np minus np naught divided by L n square plus g generation term as a function of energy and distance divided by Dn that is equal to 0. Similarly for holes you get this expressions for both holes and electrons we get to minority carrier equations and we know from basic physics the generation is equal to 1 minus R which is the whatever is left when after reflection then absorption term multiplied by the photon energy multiplied by the exponential factor which goes as a function of distance in the device right

So, depending on how you how deep you go you will have, so, absorption. So, at x is equal to 0 this will be the absorption and if you go at this little different too device the absorption will reduce as a function of this equation. So, this is what the situation is, you have now device edges of the device at located at minus Xp and Xn where there is a depletion region in the weather you the depletion region in the pn and n side located at minus W pn plus sorry this should be plus Wn ok. So, we go to next.

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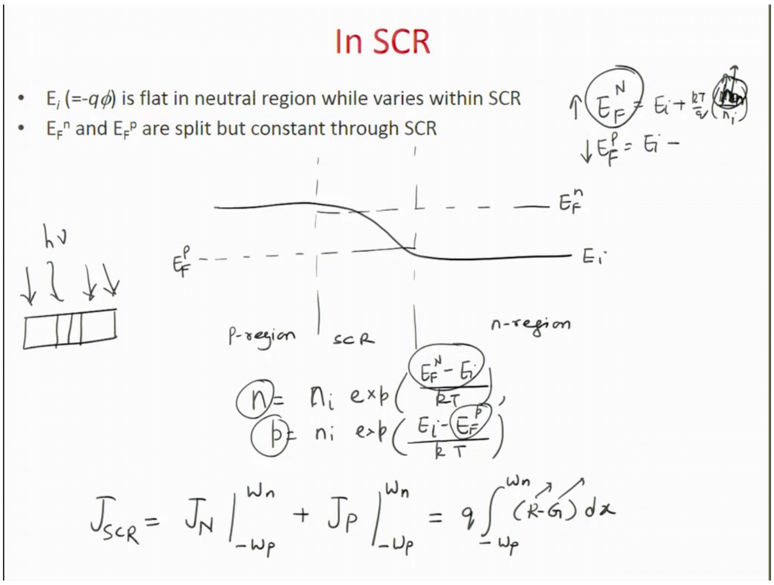

In SCR

- E_i ($=-q\phi$) is flat in neutral region while varies within SCR
- E_F^n and E_F^p are split but constant through SCR

$$\uparrow E_F^N = E_i + \frac{kT}{q}\left(\frac{n}{n_i}\right)$$

$$\downarrow E_F^P = E_i -$$

$$n = n_i \exp\left(\frac{E_F^N - E_i}{kT}\right),$$

$$p = n_i \exp\left(\frac{E_i - E_F^P}{kT}\right)$$

$$J_{SCR} = J_N\Big|_{-W_p}^{W_n} + J_P\Big|_{-W_p}^{W_n} = q\int_{-W_p}^{W_n}(R-G)\,dx$$

So, we in the next first we do for SCR analysis. So, we say that electric field the intrinsic energy level is flat neutral reason, but it varies within SCR and the Fermi levels on p and n side EF n and EF p are split, but constant throughout the SCR. So, the situation is like this. So, now we draw the band diagram of a P-N junction semiconductor. So, let us say this is the band diagram all right and within this ah. So, we can say this is the p region when this is the n region and between this we have SCR. So, essentially this is let us say the E i the intrinsic Fermi level, intrinsic Fermi level will always remain at the mid of the semiconductor.

The since the electron since n side is now illuminated with light which means n side is flooded with electron, as concentration is n side besides huge as result quasi Fermi level for. So, this Fermi level on n side. So, EF n shifts up whereas, the EF p on the other side since this is the p side the EF p on the side of lower right because this is p side region.

So, its going to be p rich the Fermi level for p is going to be lower on this side whereas, Fermi level for hole electrons is going to be.

Now, in equilibrium both these Fermi levels match right, but when the equilibrium situation is not there when you expose the semiconductor to lot of light which means you create conditions which are not neutral conditions as a result of flood semiconductor with excess carriers on both sides. So, n side becomes extremely rich in electrons, because you are suddenly excited lot of electrons from the valence to conduction band similarly the p side becomes flooded with careers.

So, as a result the Fermi level move away the electron Fermi level that is on the n side Fermi level moves up it becomes more and more electron rich, on the other hand p side becomes more and more hole rich. So, that the Fermi level moves down. And this is what we saw earlier because remember EF N was equal to Ei plus k T by q ND divided by sorry ND divided by ni. So, as ND goes up now in this case, ND is not increasing, but n is increasing. So, this was basically you can say small nn right this increases as you expose with light. So, when this increases this also goes up.

Similarly, in the other side is EF p which is E i minus this term into n pp. So, this pp will increase as a result this will go down. So, this will go down this will go up with respect to the equilibrium positions as a result of illumination these two change. So, you can say that n is equal to n i into exponential of EF N minus E i divided now this is the electron concentration term from semiconductor physics similarly p is given as ni exponential of E i minus EF p divided by kT and this these 2 increase as this gap increases.

So, the more this Fermi level shifts towards the conduction band which means n increases the more the Fermi level shifts towards a valence band p increases after illumination. So, you can say that J SCR in this case space charge region is equal to J N from minus w p to wn plus JP for minus wp to wn right. So, we have first worry. So, this is equal to q minus wp to wn R minus G dx. So, essentially what is the recombination what is the generation depending upon that your net current from the space charge region will be produced.

So, this is unlike dark situation, because situation was there is no generation there is no recombination, but now we are saying that we are throwing the. So, when you have a semiconductor device like this and you have flooded this with light. So, this is coming.

So, whether its this region or that region or this region everywhere you will have carrier generation, all across the semiconductor device you will have carrier generation which will lead to splitting of Fermi levels as a result you will have net current coming also from the SCR region.

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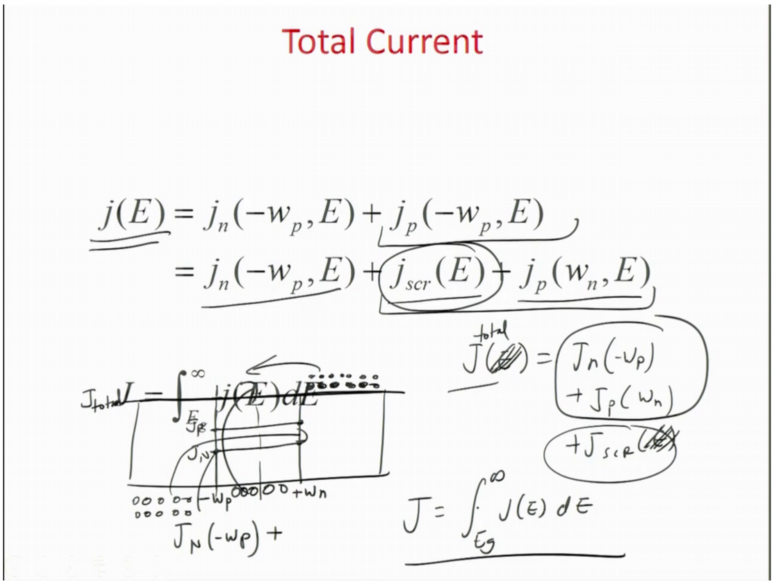

Total Current

$$j(E) = j_n(-w_p, E) + \underbrace{j_p(-w_p, E)}$$

$$= \underline{j_n(-w_p, E)} + \underbrace{\boxed{j_{scr}(E)} + \underline{j_p(w_n, E)}}$$

$$~~J = \int_{E_g}^{\infty} j(E)\,dE~~$$

So the total current in this case turns out to be if you take for a particular energy small jE is equal to jn minus wp E plus jp minus wp E and this is jn at minus wp E jp at w n E whatever is generated from the SCR region. So, essentially recently we are saying this jp in this case is nothing, but giving rise to whatever was jp at wn E at wn plus whatever is generated from the SCR region because (Refer Time: 26:12) other total current throughout the device has to remain. So, we are saying that in this case.

So, if you remember we said that this is the device this is the minus wp this is plus wn. So, we are saying that the total current at this. So, if this is J total ok. We are saying that let us say you have some electron current at minus wp which is the minority carrier, some hole current at plus wn sorry at this. If you want to locate at this particular point whatever the hole current is there and whatever the electron current is there total will make the total current.

This is fine in case of normal dark condition you can say because this condition these 2 currents remain constant within the. So, if this is J N if this is J P they remain constant within the depletion region; however, after illumination it does not remain. So, after illumination they do not remain the same. So, what we do is that, instead we are saying whatever is J P as whatever is whatever is JN at this point let us say J N this is J N at minus wp plus whatever current was here and then whatever is generated as a result of space charge it could be negative, it could be positive depending upon more recommendation or more generation, but this current is not same as this current because earlier we assumed whatever goes in goes out, but now that is not the case because you have recombination generation taking place.

So, for current to be calculated at this particular point we take the electron current. So, electrons are coming from this side to that side plus hole current at this side and what. So, holes have gone from here to here right. So, this hole current will change as it goes from here to here, similarly this electron current as it comes from as the see you flood this side with excess holes lot of holes are there after illumination and these holes will jump to this side. Similarly you have lot of electrons on the side and you will create a massive diffusion flux on this side. So, as a result now and since this region is also leading to carrier generation this side there will be change within the depletion region.

So, what we are saying now is that, this jp at minus wp is equivalent to jp at this point; jp at this point plus whatever might have come through the SCR because. So, we have to separate because we are sure about the currents at this point and this point, but we do not know what is the current in the SCR region. So, that is why we want to do it separately. So, we take the first component that is jn at minus wp and then we take jp at wn. So, this is the minority current on either side of the junction and this is what is produced from the space charge region.

If you remember that is what we wrote earlier as well in case of dark this J E was equal to J n minus wp plus J p wn. Now we added one more term which is j SCR E right this was there earlier also in the dark because these 2 profiles were flat. So, whether you take at this whether you take at this point both were similar right.

So, this is J total if you just forget about the energy point here. So, at a given energy all right. So, at a given energy in dark this was the expression in under light, since you generate more, since you generate an extra current from the space charge region because of generation recombination you add an extra current at a given position whether on this side or on that side.

So, the basically you can say that. So, J total would be whereas, this the solve will fit into j total small jE dE. So, here you are taking the energy as a function of one energy if you want to integrate them for all the if you want to get the total current you have to integrate the whole thing from Eg to infinity for all the energies.

So, now, we need to solve these equations the differential equations which I showed you earlier the minority carrier equations solution of those equations required to have boundary conditions. So, we will take the that up in the next lecture ok.

So, what we have done in this classes, we have just looked at some basic condition for analysis of light current in a P-N junction device and we have divided the semiconductor device in three regions region 1 and region 3are quasi neutral regions on pn and n side and space charge region is the is the is the junction around the junction where are you do now. That approximations remain the same how are the conditions changed because of flooding of because of generation recombination happening because of exposure to light. So, we will do further analysis in the next lecture.