Solar Photovoltaics: Principles, Technologies and Materials

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Lecture – 15
Recombination-Generation statistics

So, welcome again to this new lecture on Solar Photovoltaic Principles, Technologies and Materials. So, we will first recap the last few contents.

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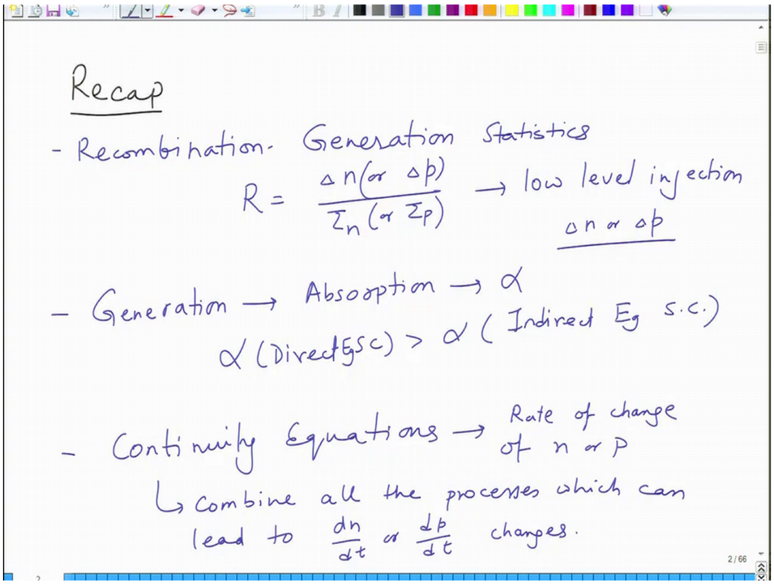

Recap

- Recombination- Generation Statistics

$$R = \frac{\Delta n (\text{or } \Delta p)}{\tau_n (\text{or } \tau_p)} \rightarrow \text{low level injection}$$

Δn or Δp

- Generation → Absoption → α

α (Direct Eg S C) > α (Indirect Eg s.c.)

- Continuity Equations → Rate of change of n or p

↳ combine all the processes which can lead to $\frac{dn}{dt}$ or $\frac{dp}{dt}$ changes.

So, in the last few lectures, we learned about recombination generation statistics. So, essentially we look that low level injection recombination rates. So, essentially you can say R is equal to delta n or delta p divided by tau n or tau p. And this is mainly about minority carriers, because any perturbation in solar cell affects the minority carrier most, as a result analysis for a carrier movement or carrier concentration or current for minority carriers is most important in semiconductor electrical property analysis.

So, we did this, this is for you know low level injection conditions, and that we explain what it was basically any perturbation delta n or delta p is a small enough. So, that your majority carrier concentration does not change much does not have significant change, whereas minority carriers concentration does change.

And then we looked that the generation basically from the perspective of absorption ok, so which is dealt with which is characterized by this absorption coefficient alpha. And this alpha tends to be high for semiconductor, which are direct band gaps semiconductor as compared to indirect band gap semiconductor and that is because in indirect band gap semiconductor because you also have to conserve the k-space and that is what leads to different kinds of transitions in indirect band gap semiconductors.

As a result not enough photon energy is absorbed. So, as a result or not enough light energy is absorbed as a result absorption coefficient of generally absorption coefficient of indirect band gap, semiconductor is generally lower than the direct band gap semiconductor. So, you can say alpha of direct semiconductor direct E g semiconductor is larger than alpha of indirect E g semiconductors. And this is as we explained is on the basis of band diagram. And then we finally, looked that we did not derive it, but we looked that the continuity equations which is basically rate of change of n or p ok.

So, essentially here you combine all the processes all the processes which can lead to dn by dt or dp by dt changes. And this means we have to take care of drift, we have to take care of diffusion, we have to take care of recombination, we have to take care of generation ok. So, these were the things that we looked that in last few lectures.

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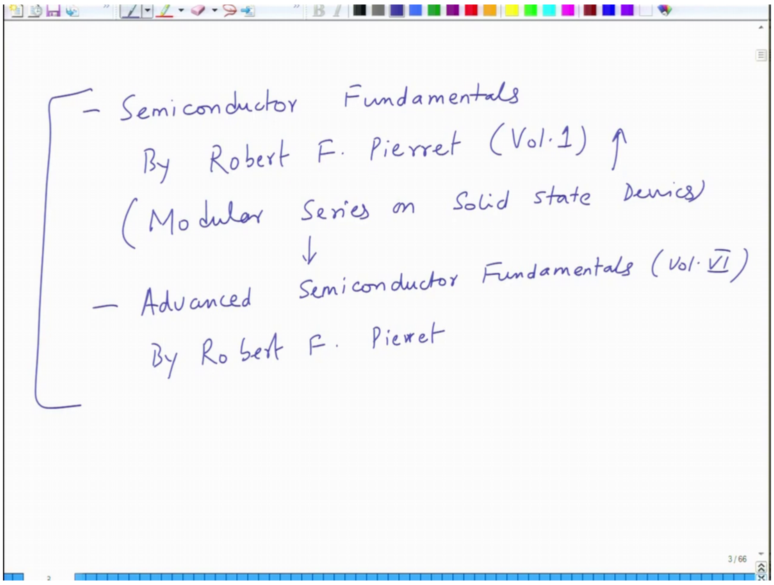

– Semiconductor Fundamentals
By Robert F. Pierret (Vol. 1) ↑
(Modular Series on Solid state Devices)
↓
– Advanced Semiconductor Fundamentals (Vol. VI)
By Robert F. Pieret

I would recommend, I would strongly recommend you to go through these two books. First is Semiconductor Fundamentals, let me just see what the exact name is this is

Semiconductor Fundamentals by Robert F Pierret. This is volume 1, there is it is series is basically you can say it is a series Modular Series on Solid State Devices. And then another volume you can have a look at it is just give the name again. And this is Advanced Semiconductor Fundamentals volume-6 again from the same series by. So, this is also from the same series both of them by Robert F. Pierret.

These two are wonderful books for those who want to improve their knowledge on semiconductor fundamentals, the band theory, the carrier action in terms of drift diffusion, in terms of recombination, in terms of generation continuity equations. And look at the few case studies where one can use these continuity equations under various combinations of recombination condition, generation condition, and electric field condition and so on and so forth. So, I would recommend you to go through these two books in detail, because we do not have sufficient time in this course to go through all the exercises, but I would recommend you to go through these.

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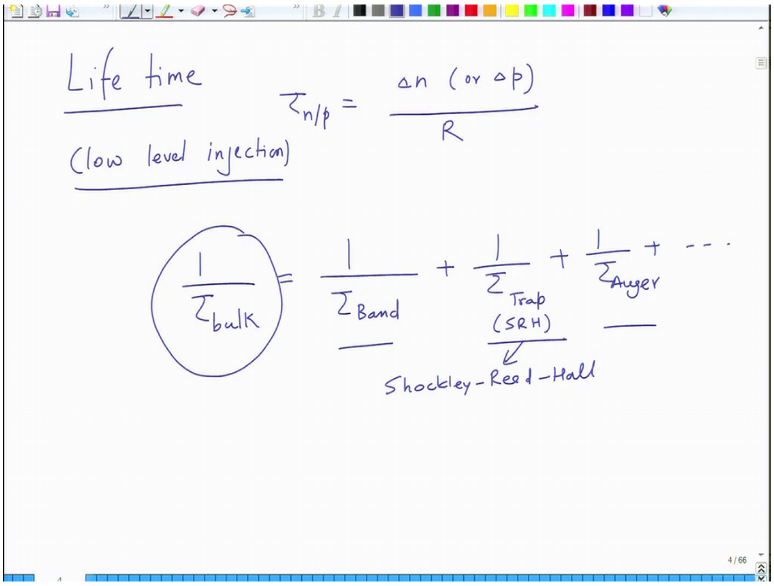

Life time

(low level injection)

$$\tau_{n/p} = \frac{\Delta n \ (\text{or } \Delta p)}{R}$$

$$\boxed{\frac{1}{\tau_{bulk}}} = \frac{1}{\tau_{Band}} + \frac{1}{\tau_{\substack{Trap \\ (SRH)}}} + \frac{1}{\tau_{Auger}} + \cdots$$

Shockley-Reed-Hall

So, now, let us begin this lecture with some more time on lifetime before we move to PNjunction. So, we define lifetime as s tau. And this was as we say delta n or delta p, so it could be tau n or p divided by the R right. And this is basically the time, and this is under low level injection ok, low level injection condition. So, basically where the number of minority carriers is much smaller than the doping and essentially what you are saying, so this is the excess number of minority carriers, this is the change in the minority carrier concentration, this is the recombination rate, and this is the lifetime.

The lifetime basically is defined as a time which the carrier is able to survive for ok. It is not the lifetime of the solar cell or Fermi conductor; it is the lifetime of the minority carrier before it recombines. So, before it recombines, how much time does it spend in the material. So, since there are many more processes of lifetime, so recombination, so one can say bulk recombination time is 1 over tau is equal to 1 over band to band. So, you can say this is for radiative recombination, then you can say 1 over you can say that trap assisted which is also called as SRH Shockley Read Hall. SRH is Shockley Read Hall after these three gentleman plus 1 over tau Auger plus any other mechanisms that may be present.

So, there are multiple, we have not gone through all the mechanisms, we have mainly gone through band-to-band recombination and trap assisted recombination. You may have Auger present especially at higher doping levels, Auger can be very critical which I will explain in a just a while. We have not discussed that earlier, but we will do that today, and there could be any other mechanisms.

So, this is how if you have multiple mechanism to recombination present in the system, you need to you can find out the you can you. So, if you want to find out the different contributions, you need to deconvolute them. What you will typically obtain is the bulk time or you can obtains, these and then go back to the bulk and so on and so forth.

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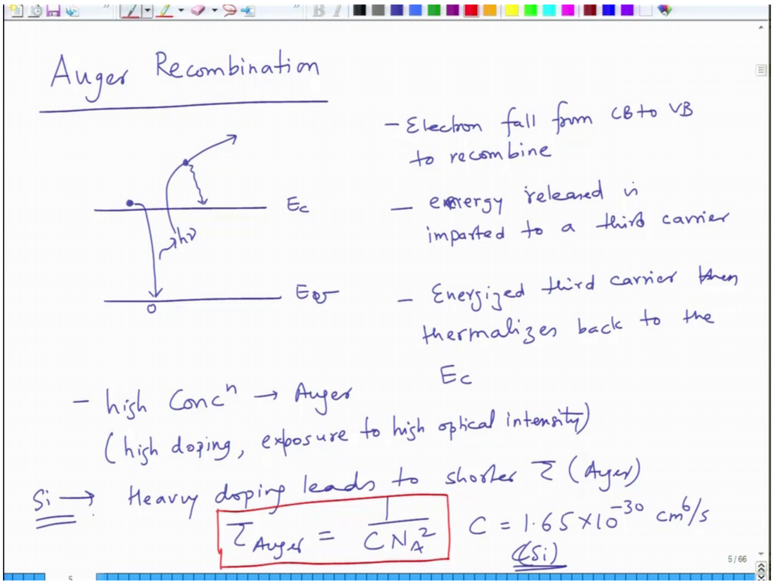

Auger Recombination

- Electron fall from CB to VB to recombine
- energy released is imparted to a third carrier
- Energized third carrier then thermalizes back to the Ec

- high Conc^n → Auger
(high doping, exposure to high optical intensity)

Si → Heavy doping leads to shorter τ (Auger)

$$\boxed{\tau_{Auger} = \frac{1}{C N_A^2}} \quad C = 1.65 \times 10^{-30}\ cm^6/s$$

(Si)

So, what is we have discussed the other two recombination and methods, the other the last one which we did not discussed was this is Auger recombination. So, Auger recombination, I do not know if you have done course on electron microscopy, but basically it is the concept is similar to the generation of Auger electrons. So, here what happens is that when you have so within a band so this is E c, this is E v, you have a electron sitting here and then you have a hole here. And this electron comes down and recombines with it, so which means it will lead to a photon. Now, this photon does not go out as a light rather this photon knocks out another electron from the conduction band.

And so this energy is spent in knocking out the electron from the conduction band which slowly relaxes back in the conduction band itself to the conduction band edge. So, basically what you are doing is that the electron falls from CB to VB to recombine ok. This is the first step. And then the emitted energy the energy which is released, energy released is imparted to a to a third carrier which is an electron all right.

And then this electron which gets energized after absorbing the energy which is released from the recombination, this energized third carrier, then we call it thermalization ok, thermalizes back down back to the E c ok. So, this is what is the this recombination mechanism is very important in high carrier concentration needs to sort of Auger recombination or when the which is basically caused by you can have high doping, or you can have very high concentrated light exposure, so exposure to high optical intensity and so on and so forth.

So, this is especially important for silicon based solar cells, where Auger recombination is very. So, in this lifetime, Auger recombination is actually the limiting factor in silicon solar cells as well as the efficiency, because this will lifetime will go to affect the current, the current is going to affect the efficiency as we will see later on how they are related. And it is this mechanism which is important in silicon solar cell.

So, basically you can say heavily doped the material is, so you can say heavy doping leads to shorter lifetime and mostly it is Auger. So, this is mainly about silicon ok. So, tau Auger is given by an expression 1 over C N A square ok. So, this is NA is basically excepted doping excepted doping concentration, and C is a Auger coefficient who is value is about 1.65 into 10 to the power minus 30 centimetre power 6 per second ok, this is for silicon ok. So, this is what is the sort of expression for the relation of lifetime in Auger recombination versus the accepted concentration.

So, you can see that the as the doping concentration goes up it goes as a square of it. So, so when the doping concentration increases, the lifetime becomes smaller in a inversely square manner, so drop will be much more faster as you increase the doping level. So, on one hand, high heavy doping leads to certain advantage in silicon solar cells as we will later on see later on, but on the other hand, heavy doping leads to higher recombination rate also.

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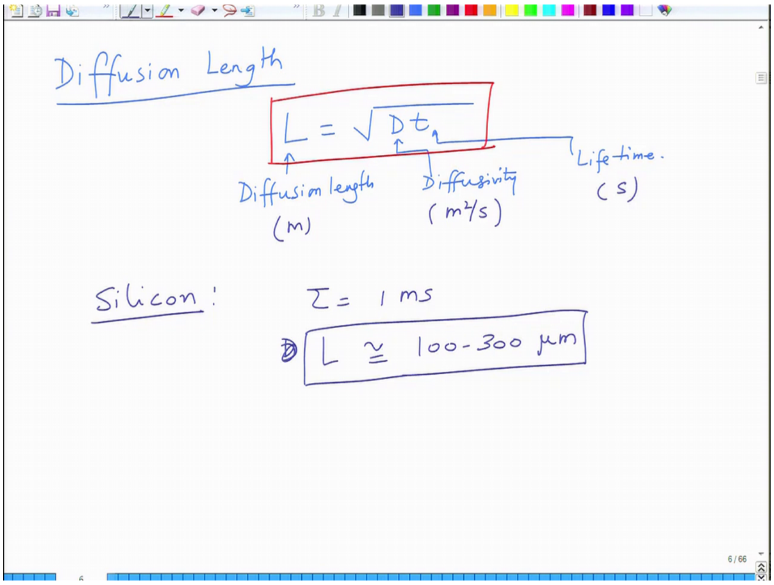

Now, we will look at so this recombination time is a relate this, this lifetime is related to what we call as diffusion length. And diffusion length is related to L is equal to square root of Dt, where L is a diffusion length, D is diffusivity and t is the life time. So, here you can see that, so if I just make it red in this fashion. So, this is diffusion length is in metre; this is in second. So, this is going to be in metre square per second, so that is the unit of diffusivity.

And generally for so what a material like silicon the lifetime is about 1 millisecond. So, it depends upon doping level and type of silicon itself as P and N type silicon. So, and this diffusivity is generally diffusion length sorry is generally of the order of 100 to 300 micron. So, your design of solar cell is basically limited by these diffusion lengths I mean you have to design a solar cell in such a manner, so that the carriers do not recombine, so that is why these diffusion lengths are very important in estimate or lifetime and as a result diffusion lengths are very important.

So, if you know the lifetime using the spectroscopic method, you can determine the lifetimes, and the lifetimes can then be back correlated with the diffusion lengths. And these diffusion lengths determine the device design, how thick the device will be to give you good enough current. So, basically these two parameters also indicate a material quality. So, higher the diffusion length is better the material quality is because for only affected by doping concentration, you may also have defects and defects also tend to reduce the lifetime. So, defects, dopants, any other factors thermal factors, so all these factors tend to reduce the lifetimes.

And our objective as a material designer is to increase the lifetime, so that the diffusion lengths are larger, and hence the carriers do not recombine. Because remember if you if you have a smaller life diffusion distance, the device thickness will be smaller. Smaller the thickness is less the light absorption will be. So, there is a competition between making the device thicker and absorbing the light. If you make the device very thick you can absorb more, but you will have no current because diffusion lengths are smaller than the device thickness, so there is. So, device also design in such a manner, so you optimize the light absorption and recombination.

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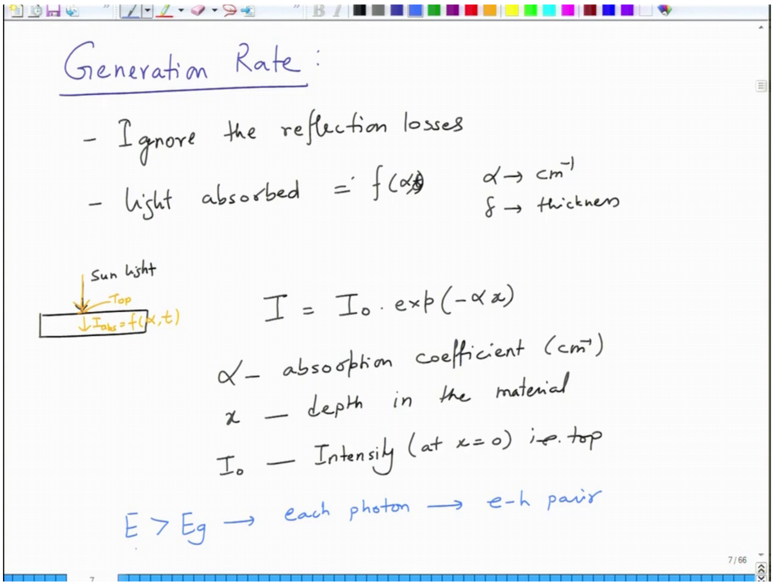

Generation Rate :

- Ignore the reflection losses
- light absorbed $=' f(\alpha\delta)$

$\alpha \rightarrow cm^{-1}$
$\delta \rightarrow$ thickness

$$I = I_0 \cdot \exp(-\alpha x)$$

α – absorption coefficient (cm^{-1})
x — depth in the material
I_0 — Intensity (at $x=0$) i.e. top

$E > E_g \longrightarrow$ each photon $\longrightarrow$ e-h pair

So, now we look at the generation rate, we looked at the absorption last time, but we look at generation rate now. So, generation rate is essentially suppose you ignore the reflection losses, all though you will have to take them into account in most cases the amount of light which is absorbed by the material will be determined by the absorption coefficient. So, light absorbed is a function of absorption coefficient.

In this absorption coefficient is given in per centimetre inverse ok. And the thickness of absorbing material which is t t or delta or d whatever it comes out. So, in this case let us say delta. So, delta is a thickness ok. So, intensity of light which arrives on the device is given by the equation I is equal to I naught into exponential of minus alpha x, where alpha is the absorption coefficient in centimetre inverse generally, and then x is the depth into the material at which you measure the or calculate the light intensity.

So, the depth in the material of concerned ok, and then I naught is the intensity on the top surface of the material. So, intensity at you can say x is equal to 0 that is top. So, essentially the you can say this is the design like. So, if you have this is sun light comes in this direction ok, orange. So, this is the top surface, then it travels down the thickness because before anything exits out ok.

So, whatever is going to be absorbed, so this I absorbed will be a function of alpha and t within this regime ok. So, this equation is basically used to calculate the number of photons absorbed and number of photons can be correlated to the number of electron hole pairs. So, assuming that each photon will give you one electron hole pair provided I is so for energy is greater than E g, assuming that each photon will give rise to electron hole pair.

If you have 100 percent conversion, then you can calculate theoretically what is the generation rate of carriers is going to be in the device, and then you can calculate. When the radiation is less than E g then material is basically transparent to that radiation that radiation will not cause any electronic transition, as a result the radiation will simply go through the material which means its transparent to that radiation that is what we call it as.

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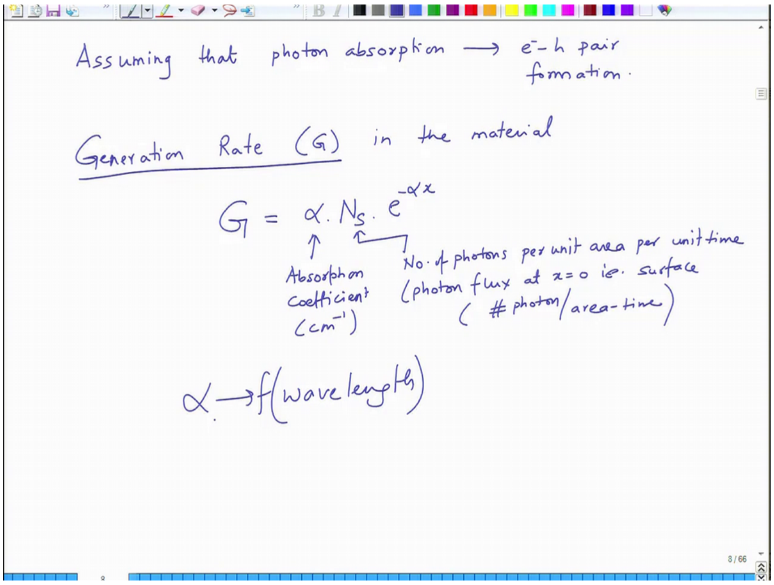

Assuming that photon absorption $\longrightarrow$ $e^- - h$ pair formation.

Generation Rate (G) in the material

$$G = \alpha . N_s . e^{-\alpha x}$$

Absorption coefficient (cm^{-1})

No. of photons per unit area per unit time (photon flux at $x = 0$ i.e. surface (# photon/area-time)

$\alpha \rightarrow f(\text{wavelength})$

So, assuming that so assuming that photon absorption leads to electron-hole pair formation, the generation one can calculate determine the generation rate G in the material of a thin basically we will consider the material as a thin layer. So, if you differentiate the above so you are now here looking at generation rate. So, for that you need to differentiate this equation that we saw earlier.

And what you get by differentiating that equation G is equal to alpha into so we can say write this as N s e to the power minus alpha x. So, this is generation rate. So, of course, it has time dependent. So, what is alpha, alpha is as we says absorption coefficient. And N s is basically so N s is photon flux at the surface which is number of photons per unit area per unit time.

So, essentially it is number of photons per on the surface right per unit area per unit time. So, we write it as photon flux at x is equal to 0 that is surface number of photons per unit area time per unit second you can say or whatever. Alpha is the absorption coefficient as we saw centimetre inverse, and x is the distance into the material. So, essentially this is the intensity.

So, here what we have done is here we took intensity ok. So, instead of taking intensity we are taking the photon flux, so that is why there is a time factor that comes into picture, number of photons per unit area per unit time. So, this basically tells you that generation rate is exponentially dependent upon the distance, and of course, it is dependent upon alpha which is a spectral value alpha. So, alpha depends upon the wavelength right as we saw alpha is dependent upon the wavelength, and then you have x.

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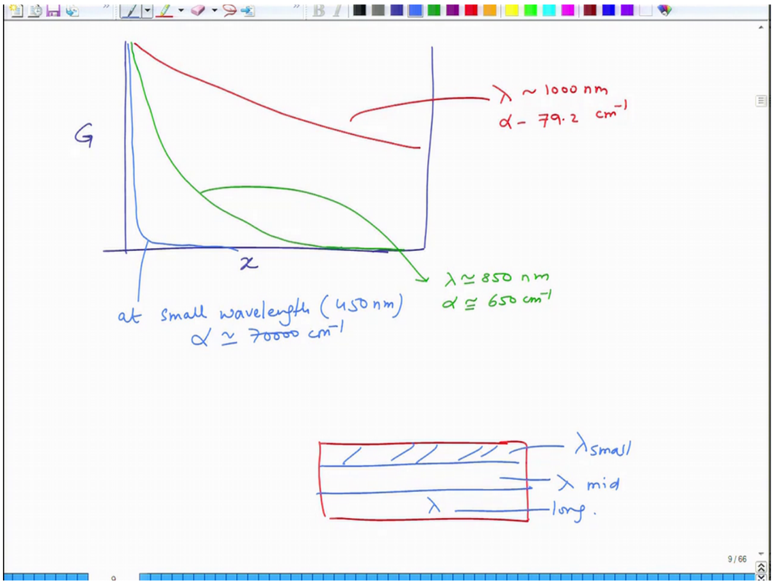

So, now, if you plot this G as a function of x, G as a function of x so let us say at a very. So, at let us say small wavelength let us say about I do not know may be about 450 nanometre and here alpha would be closed to about 70000 centimetre inverse, this would be alpha. If you increase the, if you go to higher wavelength, at higher wavelength it will appear something like this ok. So, this would be say for lambda about may be about 850 nanometre, and alpha would be here alpha reduces at higher wavelength as we saw last time.

So, alpha would be let us say about 650 per centimetre inverse per centimetre. And then at very high values, it might be something like this. So, at this lambda, this may be about may be 1000 nanometre, and alpha would be nearly 79.2 centimetre inverse. So, this would be the generation rate as a function of distance into the materials. So, you can see that shorter wavelengths are going to be leading to higher generation rate in the thicknesses which are smaller. Middle medium wavelengths will give you generation rates in the middle of the region, and higher wavelengths are going to be absorbed in the depth.

So, as you if you have a material like this; so the first layer initial layers are for lambda small, then we have lambda mid and this is lambda long. So, longer wavelengths are going to are able to travel to longer distances, because they have absorption generation rate higher even at higher thicknesses. So, all of them are going to be absorbed at, but longer are able to travel to longer distance, but shorter are absorbed only in the first few layers of the material. So, this is actually a concept behind tandem solar cells as well because when you design a tandem solar cell, the way you start the band gaps is basically determined by this only. So, you can correlate this to generation. So, generation rate basically as we said is a exponential function of distance into the material. So, this is what basically completes our discussion on carrier action.

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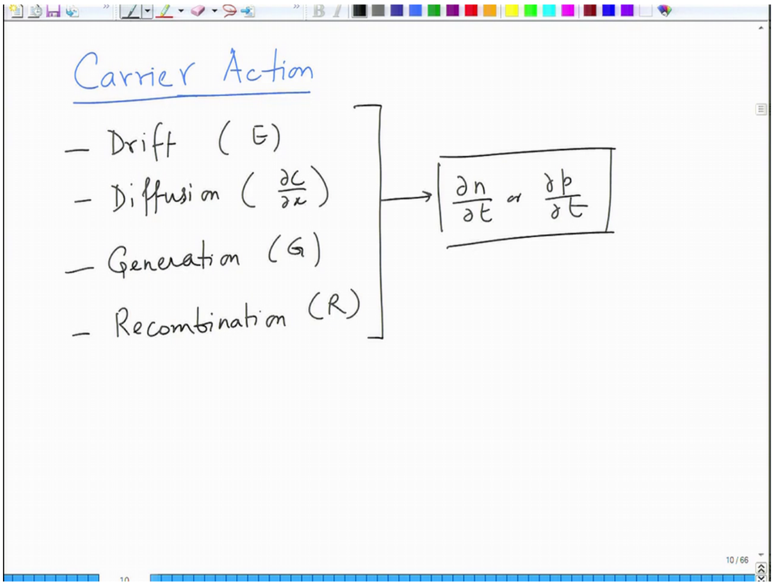

Carrier Action

- Drift (E)
- Diffusion ($\frac{\partial c}{\partial x}$)
- Generation (G)
- Recombination (R)

$$\boxed{\frac{\partial n}{\partial t} \text{ or } \frac{\partial p}{\partial t}}$$

So, we can say the carrier in the semiconductor moves by drift under the influence of electric field, it moves under the diffusion which is concentration gradient, then the that carrier concentration is also effected by what we call as generation G, and then it is also affected by recombination which is R that is the combination of these four aspects which gives rise to net change in carrier density in the semiconductor device, which is going to lead to the changes in the current that you obtain from the device ok. So, this is what the summary of past four-five lectures says.

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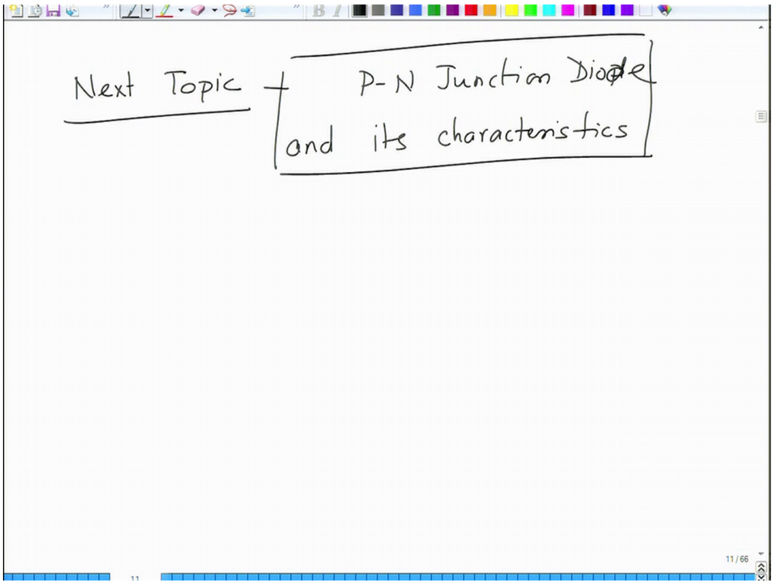

Next Topic

P-N Junction Diode and its characteristics

Now we will move onto the next important aspect of solar cells that is P-N junction. So, next topic is essentially P-N junction diode and its characteristics ok. So, we will stop here for this lecture, and we look move onto the next one in the next class, next lecture.

Thank you.