Solar Photovoltaics: Principles, Technologies and Materials
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Lecture – 13
Recombination-Generation statistics

So, good morning everyone we will again begins with a new lecture on that in this course of Solar Photovoltaics Principles Technologies and Materials. So, we will just do a brief recap of what we did over last few lectures last in fact last lecture.

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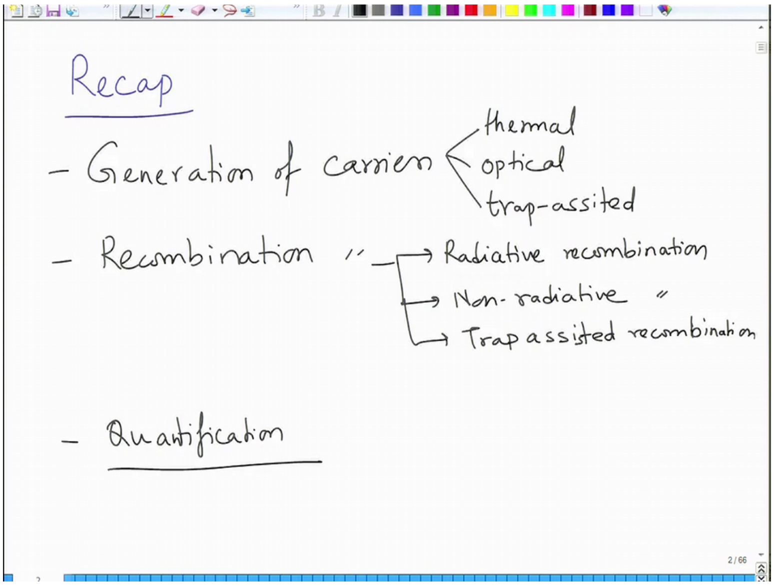

So, in the last lecture we started learning about generation of carriers in semiconductors and recombination. Generation is basically you create extra carriers in conduction and valence band and this could be thermal. So, you can thermally excite the carriers from valence to conduction band. So, that you create more electrons in conduction band and holes in valence band. And this requires that your thermal energy is higher than the band gap of the material.

Similarly, you can have optical excitation wherein you throw in a radiation whose wavelength is such that. So, that incoming energy is higher than the band gap and it excites a carrier these are photo generated carriers. So, this is photo excitation and again or you can have trap assisted. So, these are three major methods of carrier generation and then you can have carrier generation recombination.

So, carriers not only in semiconductor because it is a dynamic process. So, not only you generate carrier you also recombine carrier. So, when carrier density becomes very large then there is a strong push for recombination. So, recombination again could be a radiative recombination you can have non radiative recombination and you can have trap assisted recombination.

So, these are the methods that we saw. So, basically generation is to create extra carriers recombination leads loss of carriers. And because of these two phenomena in addition to drift and diffusion there is a net change in carrier concentration in the semiconductor which has to be analyzed which is what is useful in determining. the current in the electrical properties of a semiconductor device. And finally, we were look we were just beginning to do quantification of these recombination generation statistics. So, this is what we will take on forward so we will.

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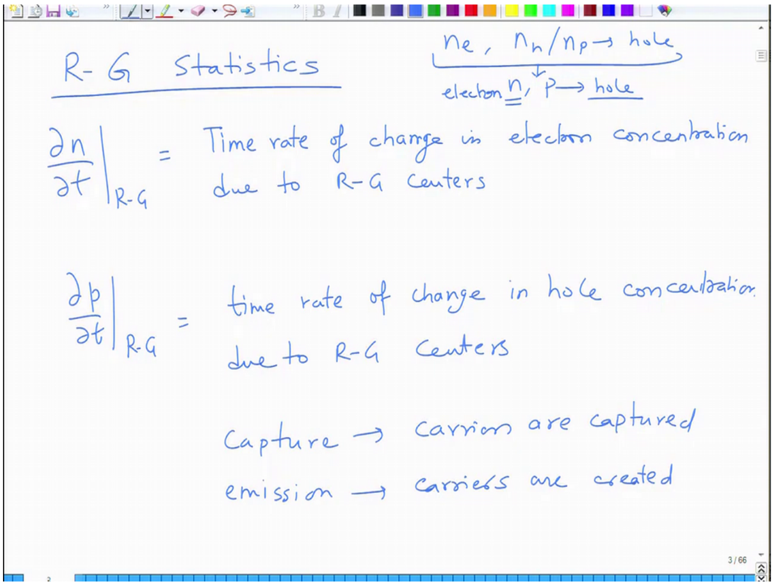

So, basically this is called as recombination generation statistics in semiconductors. So, we first defined del n by del t and we say R G this is basically time rate of change in electron concentration. So, if you recall we earlier said any is electron concentration nh or np was the hole concentration right these have been now modified to n and p. So, n is electron concentration and p is hole concentration. So, this is what we will continue with. So, del n by del t is time rate of change of electron concentration due to R G centers.

So, basically if it is negative when the electrons are lost and it is positive if the electrons are created all right. So, similarly you can have del p by del t again because of recombination generation. So, time rate of change of hole concentration due to R G centers this is where we were at the last. So, this is basically so when electrons or holes are trapped it is called as capture. So, this first term is called as capture which means carriers are captured or lost. And then another term is called as emission which means carriers are created. So, these are two terms which are often used in recombination general statistics jargon.

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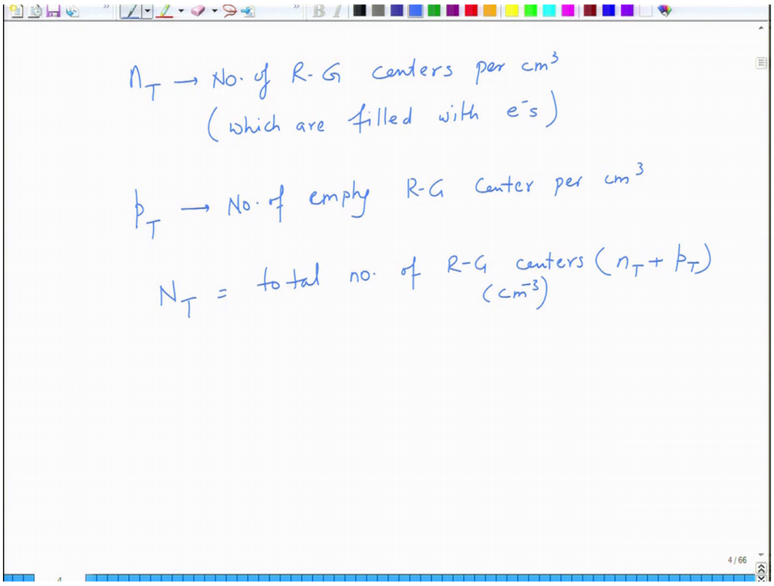

So, let us say if we define n T small Nt as number of R G centers per centimeter cube which are filled with electrons. And then we define another term capital p T as similarly number of empty R-G centers per centimeter cube. And N T capital N T is total number of RG centers which is n T plus p T per centimeter cube all right. So, this is the assumption that we start with ok. Now, let me give you some idea about another condition that we follow in semiconductor is.

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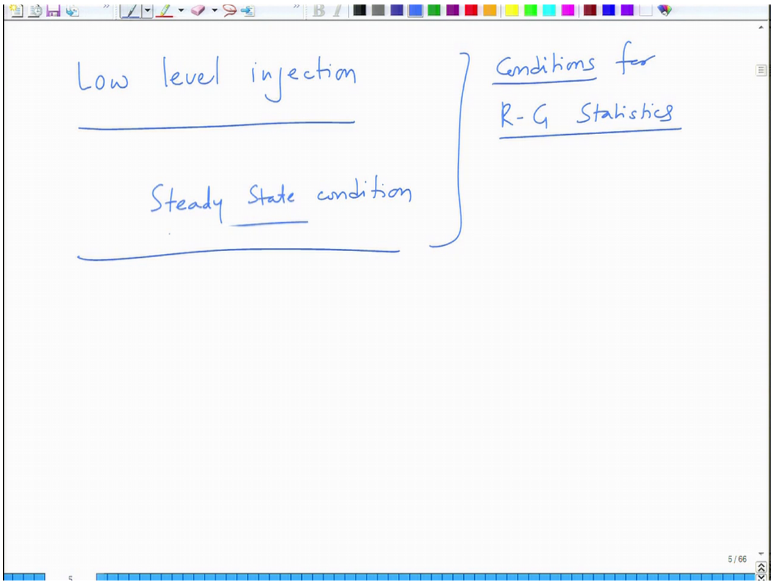

It is quite often used is it is not always applicable, but quite often it is useful is low level injection. And this we will discuss later what this condition is. So, you can have a low level condition you can have a steady state condition. So, there are a few conditions under which recombination generation is statistics.

So, conditions for recombination generation statistics we will see what these are we cannot derive everything, but we will see the expressions that come about after these equations. Now let us see first what do we mean by recombination here first.

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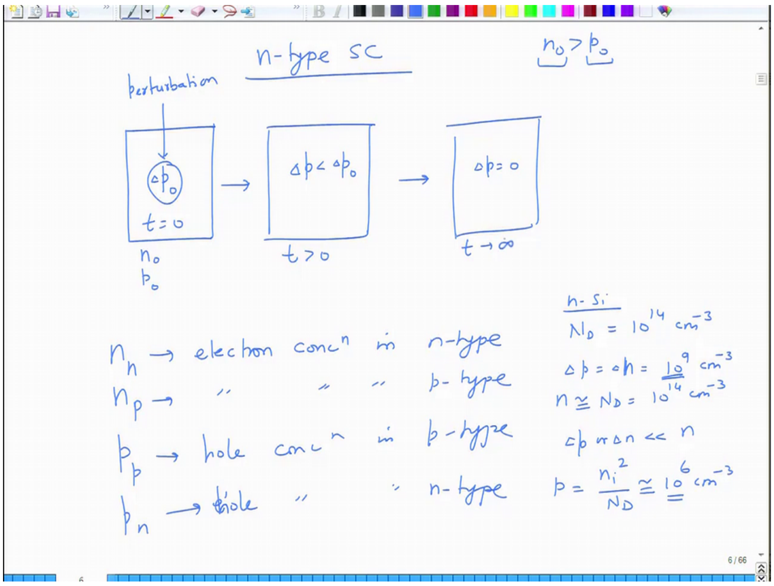

So, let us say we have a semiconductor here, which has initial concentration of you know n naught and p naught. So, you can also write it as if it is n type semiconductor. So, let us say it is a case of n type semiconductor ok. Often you will you will also see a change in terminology sometimes when you write n n it is electron concentration in n type ok.

When you write n p it is electron concentration in p type. Similarly when you write pt pp it is hole concentration in p type. And when you write p n it becomes hole concentration in n type. So, some of these subscripts will appear later as we deal with both p and n type semiconductors together.

So, let us say if this is the if we isolated if we discuss a n type semi conductor isolated I had some query concentration n naught p naught to begin with and then you create a perturbation. Perturbation is basically it means that you have you creates it could be optical perturbation it will be thermal perturbation. So, this perturbation will lead to change in the minority carrier concentration see the problem the thing is since n naught is much larger than p naught ok. If you create any change the change does not affect n naught it affects p naught.

Let me give you certain numbers. So, let us say we have a semiconductor with ND is equal to 10 to power 14 per centimeter cube this is subject to a perturbation such that. So, this is let us say n silicon all right. So, you create a perturbation. So, that delta p is equal to delta n is equal to 10 to power9 per centimeter cube.

Now, we know that if N D is equal to this much then n is approximately equal to ND which is equal to 10 to 14 per centimeter cube. So, you can see that since in n type silicon n is the majority carrier the perturbation is very small. So, you can see that delta p or delta n is very very small as compared to n, but it is now if you calculate what is p p is ni square divided by ND and ni in this case turns out to be. So, this quantity it all together turns out to 10 to power 6 per centimeter cube.

So, you can see that this perturbation is significant in comparison to minority carrier concentration. So, in semiconductors whenever you carry out a perturbation. So, it basically pn junction a solar cell is nothing, but optical perturbation you have something at equilibrium then you expose it to light certainly a lot of carriers are generated and there are huge number of carriers in the semiconductors suddenly.

So, this basically is a optical perturbation and this optical perturbation causes huge change in the minority carrier concentration that is why minority carriers are more important in terms of transport characteristics than majority carriers in semiconductors and that is why we are interested more in minority carriers than in majority carriers.

So, suppose you carry out a perturbation in this and let us say this delta p at some. So, this is at t is equal to 0 at some t greater than 0 this delta p is smaller than delta p naught and after long time, then it reaches again equilibrium this delta p becomes equal to 0. So, initially this delta p naught is very large when you create the perturbation it slowly dies down and then it completely fades away. So, this is at t tending to infinity, what happens in terms of the band knowledge?

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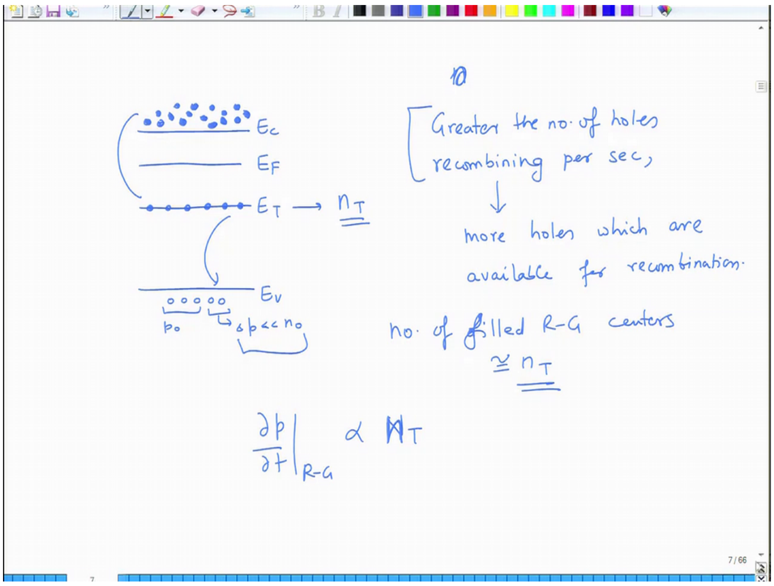

So, you have a semiconductor with conduction band and valence band. So, you have a semiconductor with valence and conduction band EC and EV. So, suppose you had created a perturbation. So, at the time of perturbation you have very large number of electrons in this. So, these are electrons and you had a few holes here ok. And let us say it is a n type semiconductor. So, Fermi level is closer to conduction band and you trap level is somewhere here this is your ET. And this trap level is filled with electrons ok.

So, what will happen in this case is so this is let us say. So, you have some electron to begin with p naught and then these are the extra electrons which are created delta p which is much larger than n naught ok. So, these are some extra you have created as a result of excitation. Now what will happen in the system is since this delta p fades away which means delta p gets. So, the electrons from the trap state will come and nullify these carriers if these trap levels are filled ok. If this trap level has sufficient number of electrons, these electrons can always come down and nullify the hole leading to annihilation of holes.

And if you have sufficient number of carriers in the conduction band, these will also get filled. Because the electrons from here if you know if you trap if you have sufficient number of electrons in the conduction band, they can always fall back to the trap center without making a much dent in the population of electrons in the conduction band. However so when you have electron coming from here to here and electrons coming from here to here the E the process is such that. So, that the trap density at this remains virtually constant.

So, whatever electrons leave this energy level to nullify with the holes which were created as a relative perturbation they will get compensated by electrons falling from the top without making too much dent in the electron population in the conduction band because electrons are very large in number already all right. So, what will happen here is your number of so basically you can say that change in hole concentration is directly proportional to that number of traps that you have present here ok.

So, if you have n T number of traps here, it is directly proportional to the number of holes which get any highlighted. So, you can right here. So, essentially you can say that that basically you can say that greater number of holes recombining per second; when will this happen? This will happen when you have more holes which are available for recombination ok.

So, when you have large number of holes available for a combination, the greater is the recombination rate of these holes because more and more electron will jump from that trap level to recombine these. So, you can say that since the number of filled RG centers let us say number of filled RG centre is approximately equal to n T which is the these are the small n T. These are the electronic trap centers and we expect this rate of change of del p by del t RG to be approximately proportional to n T sorry small n t naught capital n t. Because whatever the electrons are here they are the ones which are. So, if you do not have electrons here there will be nothing to recombine.

So, if you have depending upon the number of traps you your recombination rate will proceed. So, essentially you are not saying that all of them will recombine. But it is proportional to the number and recombination. So, basically if you have more the holes more the electrons will be jumping. So, in some sense the number of holes which are recombining here, they are the rate of those is proportional to number of electrons which are available at the trap level.

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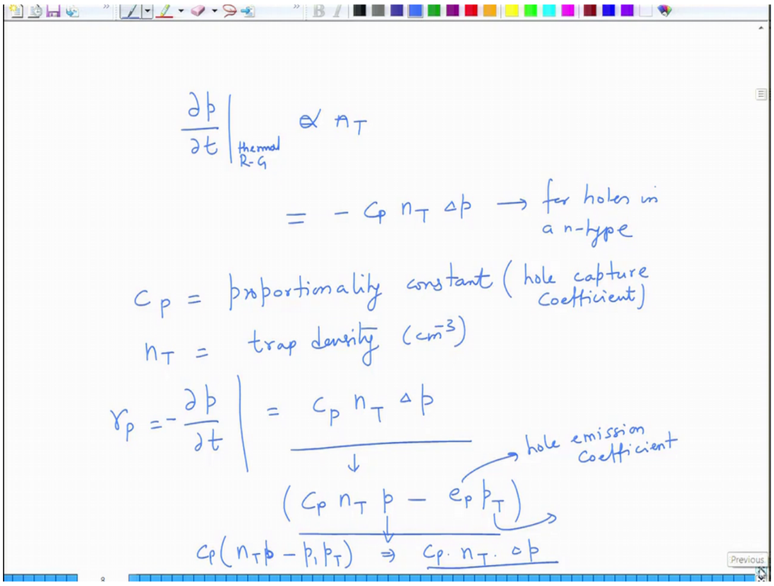

So, you can say from this let us say. So, you can say from this that. So, this del p by del t we can say this is RG you can have some thermal recombination as well. So, put together this will be equal this is proportional to small n T and this is equal to minus of Cp nT delta p and this is for holes in a n type material.

So, what is Cp? Cp is as we define it as it is called as a proportionality constant nT is the you can say the trap density in per centimeter cube and proportionality constant which is called as Cp is called as electron hole capture coefficient ok. So, this is hole in this case it is hole. So, hole capture coefficient and delta p is essentially the change in the hole number.

So, you can see that you can you can work out the units from this here. So, we will just we define this as del p by del t as rp; rp is del p by del t now this is in negative. So, what you have here is, you can say Cp n T into delta p. So, minus sign I have taken here. So, I can define the rate rp as if you look at it in more detail the expression in more detail is as if. So, this is where I have made some shortcut, but in reality the Cp n T delta p is nothing but Cp nT p minus ep p T because your electrons are the holes for electrons are not only getting recombined they are also getting generated.

So, essentially this term is equal to. So, this ep is nothing, but hole emission coefficient and this pT is nothing, but number of. So, this is hole emission coefficient and pT we defined as number of empty RG centre. So, you will always have some empty RG centers as well and p is the hole concentration. So, essentially what to simplify what we have done is we have just taken this as in order to simplify this you can just to do it as if you take Cp as common this becomes pT n minus some other constant n 1 into nT sorry p 1 into p 1 what am I writing.

So, this is equal to Cp into nT p minus some other constant p 1 into pT. And this basically and you can relate this is written as in approximation as Nt into delta p ok. So, these are some approximation that you make for these.

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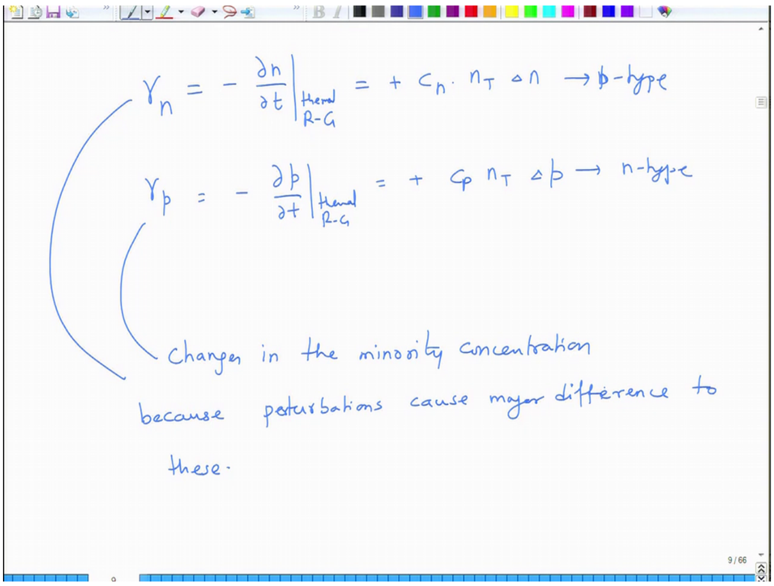

So, essentially what I am coming to is you have if you look at in totality, you have rate of electron change which could happen in p type semiconductor is minus of del n by del t R-G this is taken as minus Cn sorry plus C n n T delta n. And rp is taken as minus of del p by del t R-G you can also remove them to thermal here is equal to plus Cp n T delta p.

So, this is for n type material for a p type material and this is for a n type material. And basically what it means is that; both of these correspond to change in the changes in the minority carrier concentration because perturbations cause major difference to these they do not dent the majority carrier concentration.

So, del so if you if you want to calculate r n for an n type it would be insignifican. Similarly r p for a p type it would be insignificant. What is significant is the change in the minority carrier concentration when this happens.

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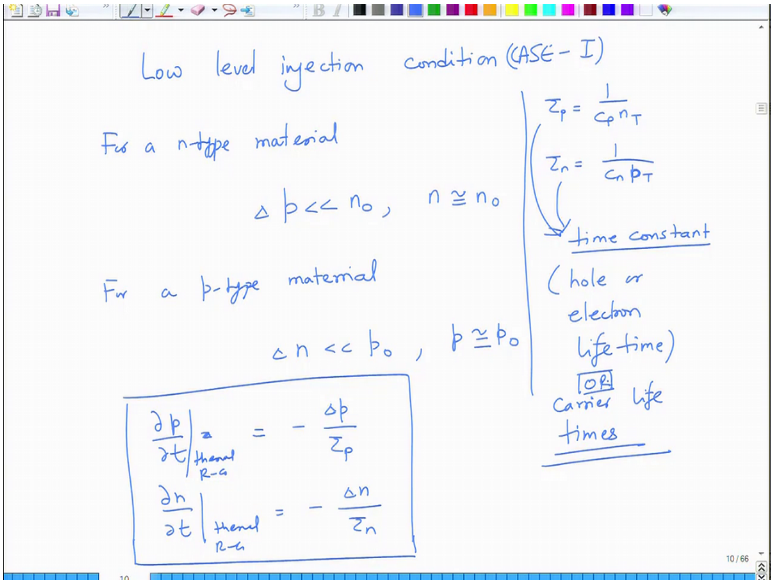

So, the condition which is followed in this is called as low level injection condition. Low level injection means for an n type material your delta p is smaller than much smaller than n naught and n is equal to n naught. For a p type material it is other way round it is delta n which is much smaller than p naught and p is equal to p naught okay this is called a low level injection.

Basically it just says that the whatever the perturbation is it is small and the perturbation causes most mostly a difference in the minority carrier concentration not in the majority carrier concentration. So, we have these accommodation generation.

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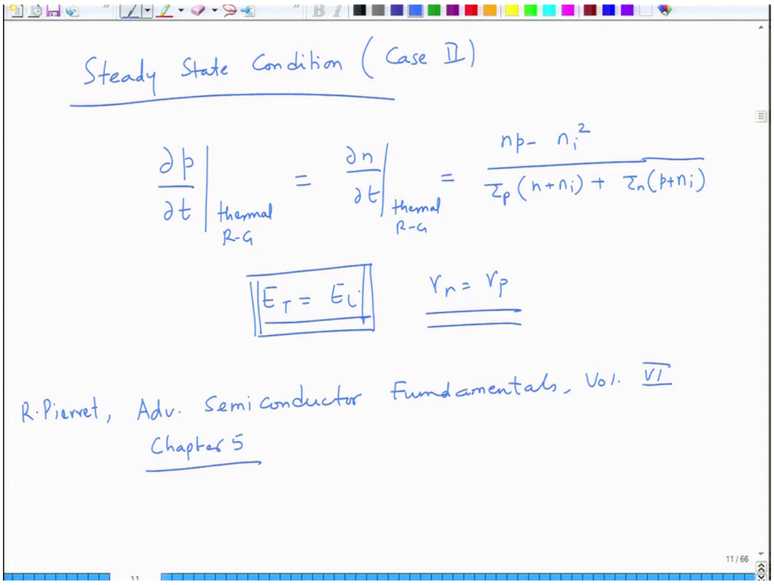

There is other condition that often prevails is called as steady state conditions. So, in the steady state condition I will not go into derivation, but del p by del t for instance is equal to del n by del t thermal R-G. And this is equal to np minus ni square divided by tau p into n plus n i plus tau n into p plus n i. So, I will explain what these taus are. So, in this low level injection condition; if you we define a once we once we accept this low level induction condition we define a quantity called as tau p ok.

This tau p is 1 over Cp nT and tau n is one over Cn nT or you can say p t ok. What is what is this tau? Tau we define as time constant this is in seconds. So, you can see from the units here you are you are you are taking this as del n by del t del n by del t is per centimeter cube per second ok. So, if this is if one of this is per centimeter cube the other thing has to be; so it has to have a unit of per second all right. So, that is why this unit of this Cp nT or Cp Cn pT is defined as 1 over tau n or 1 over tau p. And these are called as so essentially you can say for a p type material del p by del t is thermal R-G this is equal to minus of delta p divided by tau p.

And del n by del t this is equal to minus of delta n tau n ok. And these tau n are the time constants. And this is what lead this then leads us to another condition which is the steady state condition. In the steady state condition del p by del t is equal to del n by del t which is equal to np minus ni square into tau divided by tau into n plus ni plus tau n into p plus ni. And this happens when ET is equal to Ei that is the steady state condition.

I will not go to the derivation, but if you want you can have a look at this advanced semiconductor fundamentals volume VI this is by R. Pierret. So, in this chapter 5 deals in detail with recombination and generation statistics. So, this is what basically the recombination generation statistics in brief is. There are other cases as well which we can deal with, but we will we do not have time, but another one.

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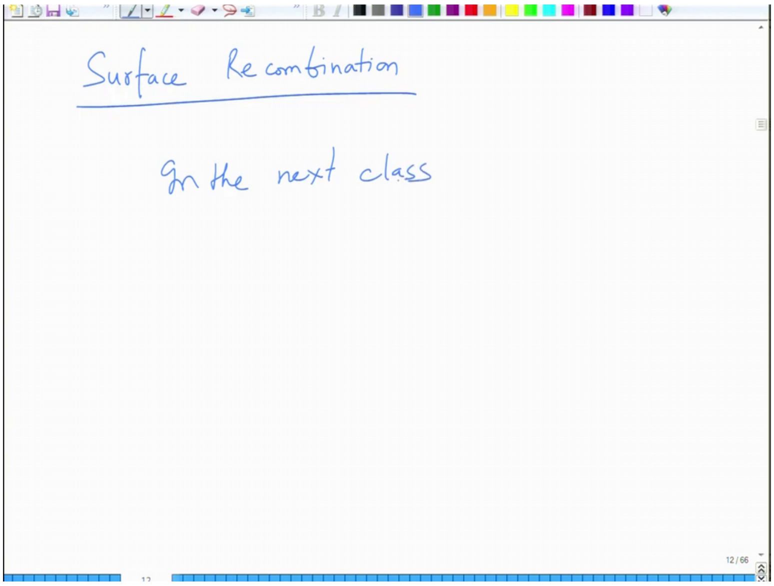

So, one is this trap assisted recombination, second recombination generally that happens is surface recombination. So, you can say this low level injection condition is the case-I. And a steady state condition is the case-II, which is when this ET is equal to Ei. And what it also means is that basically r n is equal to r p in this case. And tau n and tau p are essentially you can say these are time constants you can say these are hole or electron life time. The time for which electron a hole is alive and these can be determined experimentally.

So, similarly so these are the lifetimes of carrier lifetime as we call them carrier lifetimes ok. So, these are different condition that prevail inside semiconductor devices. So, now, let us go to surface recombination. In the surface recombination surface is important because every material has a surface. So, we are running out of time for this lecture. So, we will take up the case of surface recombination in the next class.

Thank you.