Optoelectronic Materials and Devices
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Module - 3
Optoelectronic Materials Device Physics
Lecture - 30
Continuity Equation

Today, we are going to continue on what we have learnt about carrier actions and semi conductors. Basically, we learnt about generation of electron and holes recombination their response to the electric field drift motion and the diffusion motion. Now, it is time to see how all these things take place in a semi conductor material or a device, which then finally gives rise to a device characteristic.

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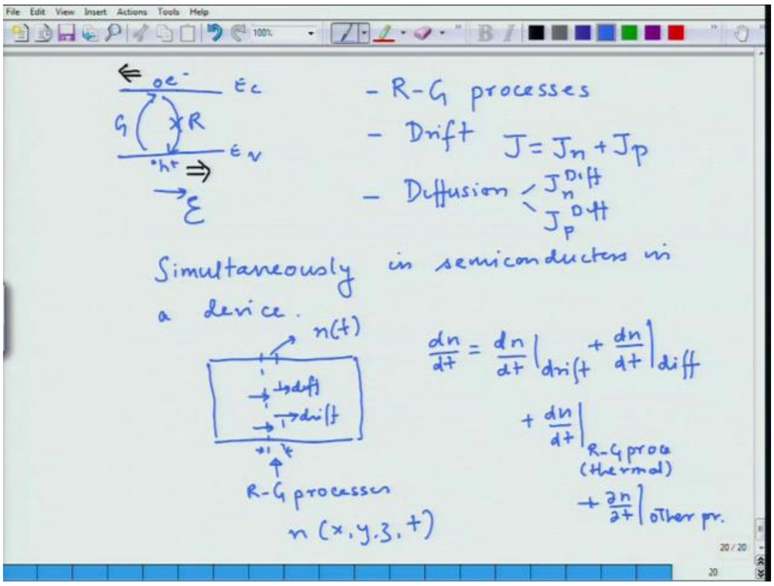

So, to summarise in previous lectures what we have learnt about a carrier action is R G processes recombination generation processes in which we learnt that from conduction band and valence band. We can generate carriers and we can in this process we generate that is generation of carriers and when these recombine, this is recombination process. We learnt different mechanism, which make the R G processes possible and we also learnt how to a take into account change in the carrier concentration due to these processes.

We also learnt about drift, which was response of the carriers to electric field, which basically means if there was a field applied in this direction. This would mean that electrons are going to move opposite to the field in the conduction band and the notional holes that we talk about are going to move in the in the direction of the field. Hence, we can write about the current as due to electrons in the conduction band plus the current density other than current and holes in the valence band.

Similarly, we also learnt that if you do not have uniform carrier concentration in the device then we will also have a diffusion process, which would also lead to current due to diffusion and again this will be due to electrons and due to holes. So, far we learnt about these processes as individual processes, but when we talk about a device all of them are occurring simultaneously in the materials. So, all these processes works occurs simultaneously in semi conductor materials in conductors in a device.

And hence we need to find a way of dealing with them at the same time what is happening in the material. So, if we consider all of them together what we can talk about is let us say if I have a semi conductor and so far I am not trying to bring in the device, but if I have a semiconducting material and at any particular point and let me think only for about one dimension right now. I want to figure out how is the concentration of electron changing with time here or I could also say that how the concentration of holes is changing with time here, but let me just talk about electrons right now.

Then I can say that change in this particular segment of a material change with time is going to be a resultant of all the processes that we have talked about, which means how many of the electrons due to some if there is a field. Here are going to go out or how many will come in it would be a result of how many due to drift it would also be a result of how many are going to change due to diffusion minus, how many will come in net value of this will give me a change in the electron concentration here.

So, I can write that those two processes in terms of d n d t drift due to drift process due to response of the field assuming there is the field here at the moment plus. So, we are writing a general equation change in the electron concentration due to diffusion net electron concentration in this segment due to diffusion plus at the same time. We know that we can have processes here the R G processes, which would lead to generation or net annihilation of the carriers.

So, that would be additional term which would lead to change in the concentration it is a term like source or sink for mass or heat continuity equation it is a similar term for electron carriers in this context. So, this we would write for R G processes and generally when we talk about R G processes this is also what we are talking about, which are mainly thermal processes. Then we split out another term for generation which may be due to external sources, which is change in the carrier concentration due to other processes.

What are these other processes as we discussed the generation can be due to thermal reasons or the generation can be due to the injection of carriers or due to excitation by a light source. So, this would be a general equation, which is basically having four terms drift diffusion R G processes, which are thermal processes leading to change in carrier concentration at that point or other processes. We have plotted in this manner, but you can think of it, this is an in general, it will be a concentration of carriers will be a function of its position in the material and time and hence the equation is going to be in general terms.

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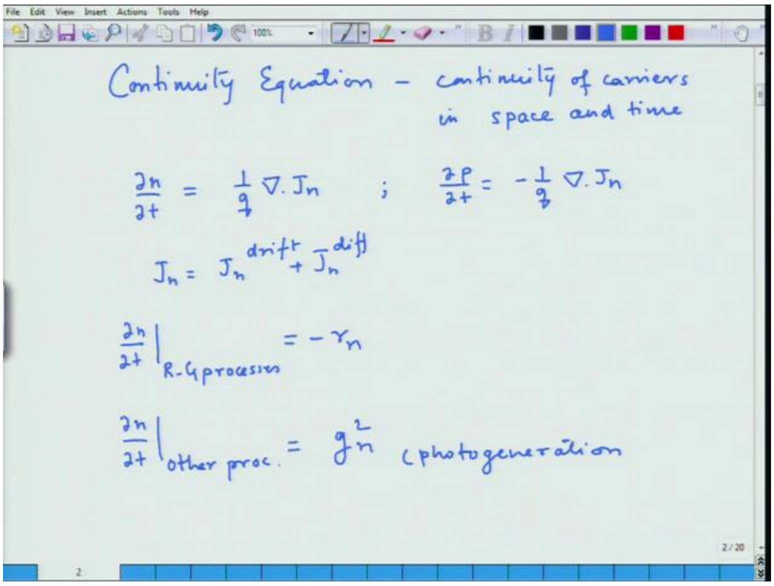

So, now if we look at it and try to figure out what this equation means, let me look at it in terms of overall continuity this equation is basically a continuity equation very similar to what we have in mass and heat a continuity equation. It is continuity equation for carriers and semi conductors, it is providing information about continuity of what is happening at a given point in the semi conductor and in time also continuity of carriers in space and time.

So, this general equation that we wrote earlier tells how the carrier concentration at a particular point is related to the carrier concentration to its adjacent point and how it is changing with time. So, that is a general equation if we try to make it a little bit more simplified, then we know that change in the concentration if we take the first term due to a drift and diffusion. We know that the change in carrier concentration can also be written as if there is going to this is going to be the gradient of the electric current due to electrons.

Similarly, one could write the counter part for holes and the whole equation has to be written. Where this would be given by negative charge and you know the source for the negative charge is because conventionally the current is taken as the flow of the positive charge and for flow of the negative charge it is a it is the direction is negative to the flow of the negative charge. So, if we write the change in concentration in a general term then this can be further specified what is J n J n here is overall J n due to drift plus J n due to diffusion and you can write equivalent terms here for holes.

Similarly, the second term, which is the change in the concentration due to R G processes. We make a short form of it and write it as negative of as if this is basically recombination of carriers or loss of carriers. So, we give it a symbol r n and for the fourth term, which is a change in carrier concentration due to other processes for most of the discussion in this course. We will limit it to only photo generation, which is given a symbol here as g L n so this is we limit other sources to only photo generation.

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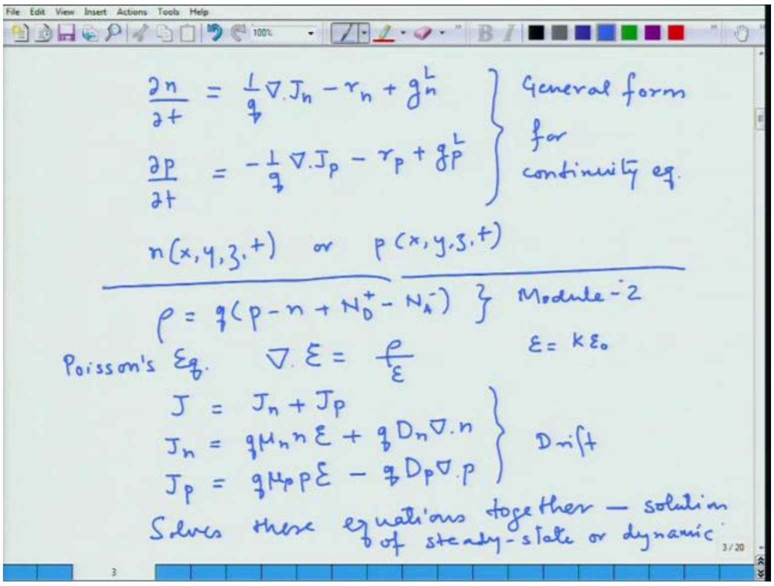

So, if we take these short forms for the continuity equation then we what we will find is that the continuity equation can be written in short by del n del t is equal to 1 over q gradient of the current due to electrons plus the generation if it is confined to the photo generation only. The counter part of it for holes will be written continuity equation will be written as del p del t with be negative of 1 over q gradient of the current density due to holes minus a thermal R G process term plus g p L.

So, these this is my general form for continuity equation this is the general form for continuity equation, which is a simplified form for optoelectronic devices. Now, this is the starting point for analysing the devices. If I need to know in a device what is a behaviour I would like I would need to solve these equations and try to figure out how what is the change in x y concentration of carriers as a function of where it is and as a function of time.

So, this is the this is basically the beginning of the analysis of the device, where we will take the all the carrier actions in the semi conductor into account and figure out what would be the device characteristics. And by using this equation I can solve for n x y z or P x at any position in the device and also the function of time. Now, these are not in themselves sufficient because we need additional information. So, let us try to see what all we know, which the equations that we need to solve in order to find a solution in a device.

So, if we summarize all the equations that we need to solve then we know initially we learnt in a in addition to these equations. We need to solve that the charge density at any point in a semi conductor will be given by the number of electrons plus will be given by the number of holes minus the number of electrons plus the number of donors ionized positively minus the number of acceptors ionize negatively. This would be given by charge density if we know the charge density in the semiconductors.

The next equation that we need to know is the Poisson's equation that solves for which is a differential form of the Gausses equation, which looks for the gradient of the field is given by a charge divided by the dielectric constant where dielectric constant in a material is relative. Dielectric constant and the electrical electric permittivity of the vacuum in addition to that we have learnt during drift that current due to electrons is current due to electrons due to drift, but prior to that.

Let me make a general statement the total current density would be current density due to electrons and due to hole as if electrons are moving independently and holes are moving independently in the conduction and valence band respectively. A current density of electron is going to be given by the drift term, which account for the mobility of the electron and the electric field plus a diffusion terms, which accounts for diffusion, coefficient and the gradient of the electrons.

Similarly, the current density due to the holes will be given by the drift term minus the diffusion term for the holes. So, this we learnt during our discussion in the drift lecture. This we have learnt earlier in module two and then finally, we have come up with the continuity equation here. So, these equations together when we one solves when one solves these equations together and finds a solution of steady state or dynamic or dynamic behaviour of the device.

So, that is this is why we say this is the starting point of device analysis any device in analysis starts from these equations and they are you can see interdependent on each other. Hence, they all have to be solved simultaneously in order to find a solution and this what the starting point of many device simulator is which are existing commercially also, but one needs to know this basic knowledge in order to use them and find a solution to various device characteristics. Now, we would like to simplify this problem and talk about a simple solution here because computer simulations are not possible over here.

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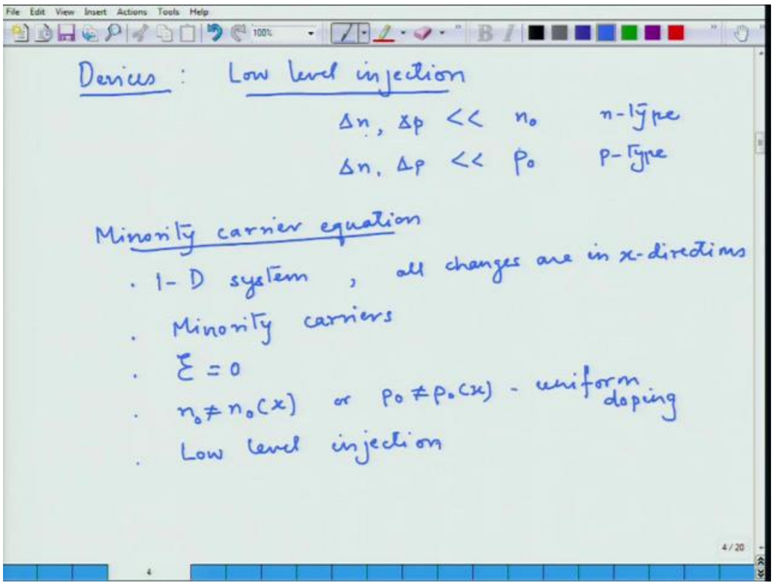

So, we will look at special case of this continuity equation and which is very common in many devices and which we will also use later in the course and that is for the situation. When we have devices, where we have the state of low level injection what does low level injection mean? We have earlier come up across this term when we were talking about generation of carriers. It basically means, if I am generating electrons or if I am generating holes their concentration is much less then the majority carrier concentration n 0 if this is a n type device, n type semiconductor or if it is a p type semiconductor. Then the excess carriers generated are always much less than the majority carrier if it is a p type semiconductor.

So, for many devices the situation is true so we find simpler form of the continuity equation that we will solve easily and use certain assumptions. So, we will make some assumptions to find another form of the continuity equation, which is basically used for minority carriers and their low injection level. Basically, we can say that number of in this situation the number of minority carriers generated are going to be important because number of majority carriers generated are so much smaller to the majority carrier concentration.

That it is not it is not going to make a huge difference, but the number of minority carriers would make a huge difference. So, we are analysis is getting limited to the minority carrier. Minority carrier equation and in the simplified form from general continuity equation we are going to make certain assumptions for this equation. First of that is again we will assume a one-dimensional system, which basically says that all our carrier concentrations are changing only in x dimension. So, all changes are in x dimension in x direction another directions things are relatively constant.

We also make the assumption that we are only looking at minority carriers here and we are looking at a situation where electric field generated is 0. So, there is no electric field in this particular simplification and we also make an assumption that the at equilibrium n is not a function. The equilibrium concentration is not a function of x or for p type it is not a function of x again, which means it is a uniform doping further assumption we make its a low level injection, which I have already mentioned. So, for low level injection you are going to solve this equation or simplify the continuity equation. So, it is low level injection situation and we will apply these conditions to see what will happen to the continuity equation.

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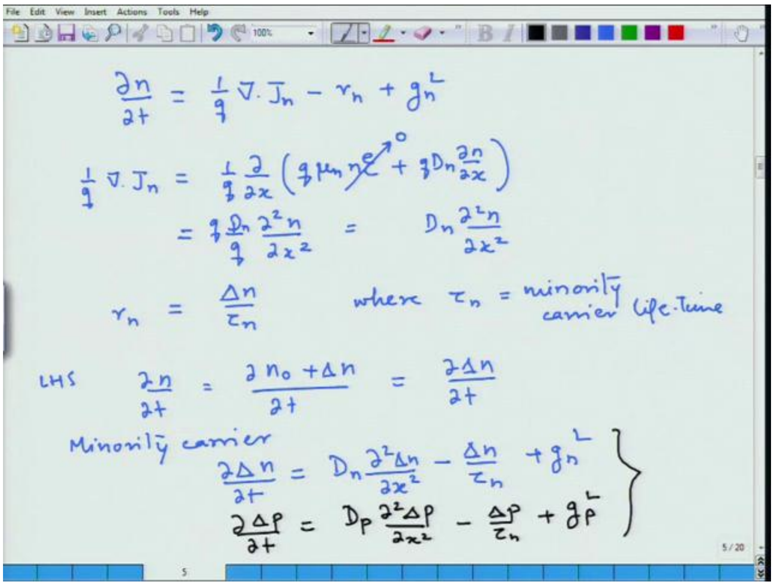

So, if we continue that discussion again lets write the general form of the continuity equation here, which is we have simplified to and let us look at all the terms on what is happening in each of these term. And if we follow that, then let us look at the first term here on the in the right hand side. So, 1 over q gradient of the electric the of the current density due to electrons is going to be 1 over q and since the problem has been simplified to one dimension. I can only worry about del over del x and expand J of n this is going to be mu of n, n electric field plus q diffusion coefficient for electrons times del n del x.

Now, immediately you can see since we have said that there is no electric field this term is going to go to 0. So, we are going to simplify this as n q of d n will come out, which would give us q of d n. So, finally term would be d n gradient of x square if you look at the term r of n, r of n we have done in the recombination generation under the low level injection. A recombination rate for a low level injection can be written as del n of tau over n where tau of n is basically minority carrier life time of the material.

Simplifying, this to these situation then we can write the left hand side of this equation del n del t is nothing but equilibrium concentration plus the excess concentration divided by del t. Since, we have equilibrium concentration is not changing with time this would be simplified to the excess concentration to del t. Similarly, I can write make the this similar analysis for the second and the third term. Then I would write the overall continuity equation for minority carrier for minority carrier continuity equation will be del n rather than writing for the total carrier concentration.

We write a equation for excess carrier concentration, which is going to be given by D n second derivative of the concentration gradient plus g n. So, I have changed and similarly I can write for this as well for the excess carrier concentration. So, what we have done here is we have changed the continuity equation for from equation, which is written in terms of the carrier concentration or electron concentration to excess electron concentration and which basically means then we are solving for what is happening to the excess electron concentration in a device.

A counter part of this can be written for holes also, which would mean this is going to be for minority carriers this equation will be written as D p for x is hole concentration given by. So, this is so these two equations are for minority carrier continuity equation, which would be solved for many situations.

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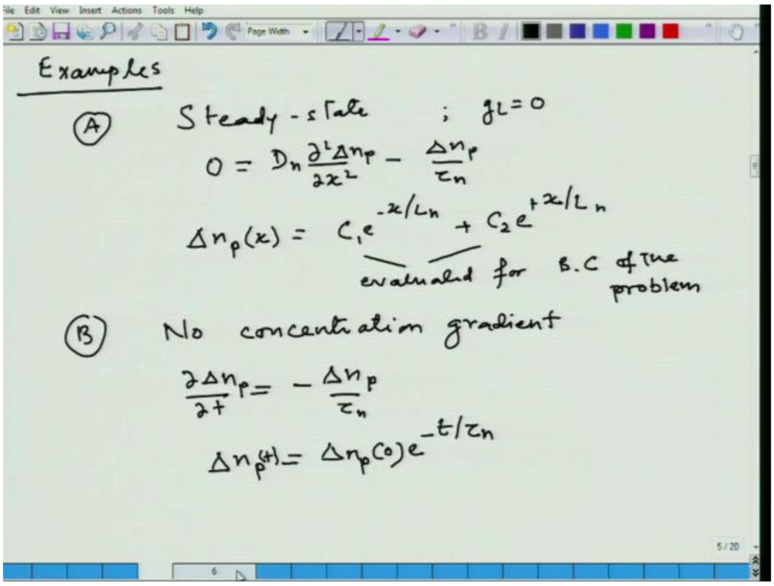

Let us, take some examples, so we will take the first example and apply it to get some solution. So, the first examples here are the first one is let us say if I apply look for a steady state solution if I am looking for a steady state solution what will happen to the minority equation and concentrating on the first one, which means the first term here is 0. So, for a steady solution this will become 0 and the second term will remain and that will be D of n second order differential.

Second derivative for delta n minus delta n p over tau n and this the solution for this can be obtained there is a possible solution and this you can look up in any solution book what is a what are the typical solution for such a equation and assuming here the photo generation is 0 g L is 0. Then typically solution for the excess carrier concentration in p will be of the type which is given by L n plus c 2 exponential minus x over sorry plus x over l n.

Then this is the constants which need to be evaluated for a given boundary condition, then there are certain other approximations that we encounter often in the device physics and the second one is when there is not concentration gradient. So, when there is no concentration gradient what will happen to the minority diffusion equation. In the no concentration gradient the term this term will become 0 and you are left with the transient of the excess the function of time. This one becomes 0 is equal to and the a solution for this type of differential equation is typically is basically delta n of p at a given time t given by what is the carrier concentration at time 0 and it is reducing with the time constant of the life time of that carrier, which is in the p type material.

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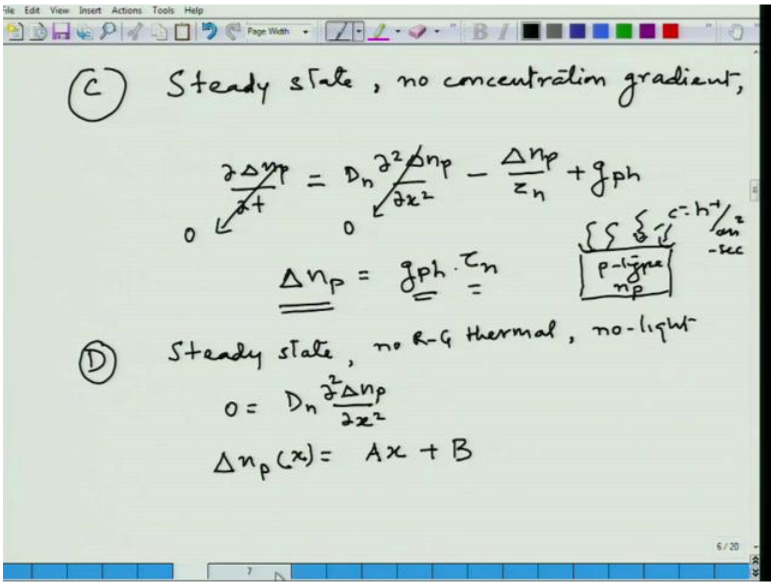

So, you can see how we from a general equation we can get some very simple close solution for under certain approximation. The next one is the next approximation or example is when we have a problem, which is in a steady state and there is no concentration gradient and in addition there is no generation of photo carriers this is also 0. If I am looking at this situation then what happens to the this the solution I am left with basically del the left hand side is equal to this is actually already steady state. So, this is also going to 0 there is no concentration gradient.

Hence, the second term which is the second derivative is also going to 0. I am only left with the third term and I have already said that the now this is wrong sorry this the photo generation is there. So, this would be this would be under the condition where there is photo generation and if I look at now this equation the solution for this is simply the change in the carrier concentration is given by the amount of photo generation multiplied by the life time.

So, this is a excess carrier I generate this is a very simple problem which has a very simple physical interpretation what am I saying I am saying here I take a semi conductor in which I am looking at the change in the carrier concentration. Let us, say this is a p type semi conductor I am looking at the carrier concentration of electrons in the p type material and I am shining light on it. I am shining light and it is creating certain electron and hole pairs at some rate per second.

And I continue to shine eventually the electron and hole concentration in the semi conductor will increase. That will increase the recombination rate for those carriers and then it would eventually lead to a steady state hence I say it is a steady state solution. The first terms goes to 0 and then say I take a material for which I am shining light sort of uniformly everywhere. So, it is not that there is more carrier concentration here compared to here so if I am shining light uniformly the second term also goes to 0, then I am only left with the third and fourth term, which has a simple solution that the excess carrier.

The excess is steady state that I am generating is equal to the rate at which I am creating the excess carrier multiplied by the life time of the electrons or the minority carrier in that material. So, this is a problem which you will encounter again when we come to the next module and we have a solar cell and we are trying to see how many carriers are generated there. Let us, look at one more example special case for the minority diffusion equation and this one is when you are looking at in a steady state where it is no R G thermal process and also there is no light, which means the first term the third and fourth are 0. I am only left with the equation, which is a second derivative of the excess carrier concentration.

Now, a solution for a such a equation is very simple its basically the excess carrier concentration in x will be given by some constant times x plus B. So, we have looked at four different situation in which I can apply the minority diffusion carrier equation and find a close solution, which is also physically meaningful and I we looked at one case of a generating how many excess carriers are generating generated in a steady state when I shine light on a semi conductor. So, at this point let me summarize all the equations that we have learnt so far.

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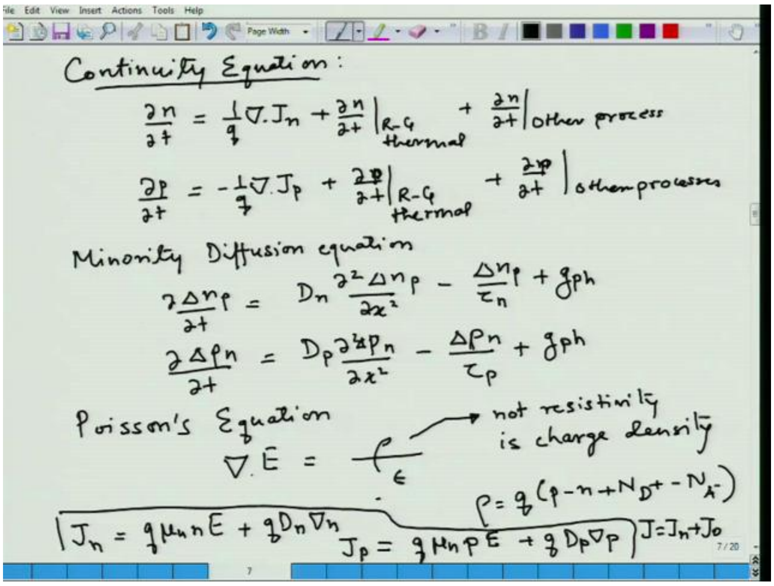

So, far we look at all the processes that are happening in the semi conductor and we stay well we cannot destroy or create carriers. Hence, you must have a continuity equation and writing it for both the type of carriers because in semi conductors the overall current is addition of current due to electrons and holes. So, I will write continuity equation for the for both the type of carriers so the change in this is going to be given by in its short form 1 by q gradient of the current due to electrons plus del n del t due to R G thermal plus del n del t due to other processes.

Similarly, I will write for holes because they are both work in independently they have to be solved independently both equations. I will solve for hole concentration which is R G thermal plus del n del t sorry del p divided by other processes. Now, this is the general form of the equation and then we reduced it to some simple approximations and gave the equations for minority diffusion under the approximation for minority carrier diffusion equation. In that a approximation we showed that the first these two equations will reduce to basically the excess carrier concentration being given by the second derivative of the excess carrier concentration by the life time of the minority carrier plus a photo generation.

Similarly, I would write it I would solve it for holes also and this will be given by for the diffusion of holes. The second derivative of excess hole concentration in n type material minus the x the recombination due to thermal processes and a photo generation. Now, in addition to these equations we also need to solve another equation, which we have not discussed so far and that is if I look at this particular expression. The general equation I am solving for the n and the p in the in the first equation and then I will look for the current due to electrons and holes, but remember the current due to electron and holes is dependent on the electric field.

And electric field itself is changed when the change the there is a change in the density of charged particles in the material. Hence, it is a one uses the value of electric field in this equation, which itself depends on the value of n. So, you are solving something which depends on itself so it is kind of a iterative solution one needs to look for and in order to do that. We need to calculate for every solution that we find we need to calculate, what is the change in the electric field?

And so how do we calculate the electric field and for that we use another equation, which we have not discussed with the equation of state, but it is needed to solve the continuity equation and that is known as the Poisson's equation, which relates the electric field in the semi conductor. The gradient of the electric field is given by the charge density divided by the dielectric constant of the semiconductor. What is the charge density?

Now, keep in mind this is not resistivity although the symbol is same this is not resistivity. This is the, it is charge density and in a semi conductor then rho is equal to, the rho is equal to a charge on the holes minus. The charge on the electrons and the number of holes minus the number of electrons plus number of donors ionized donors minus the number of ionized acceptors. So, this is a charge in the semi conductor, which we need to feed in this equation to calculate E and then this electric field is used in this continuity equation to get the value of n. Once, again once you get the value of n you have to again calculate E and finally, the solution will converge to a value and that would be your final solution.

So, we use the Poisson's equation in order to solve to solve this. The other supplementary equations that I that I used here and that we have been discussing earlier the current due to the electrons is given by nothing but q times due to drift electric field plus due to the diffusion of the carriers the gradient for n. I can write the same things for current due to the holes will be given by charge, mobility number of carriers, field plus the gradient for the holes. And finally, when we write the expression for the total current I am going to add these two up.

So, the total current is going to be the current due to the electrons plus the current due to the holes in a semiconductor system. So, this is what we have come to after discussing all sort of actions that the carriers in the semi conductors. Undergo we have come up with a set of equations, which we can now apply it to a problem and see what will be the solution. So, let us see an example of how we will look at this problem of using this equation to solve our problem. Since, we have not started discussing devices as yet let us take up a problem, which is only related to semi conductors and the processes that are happening.

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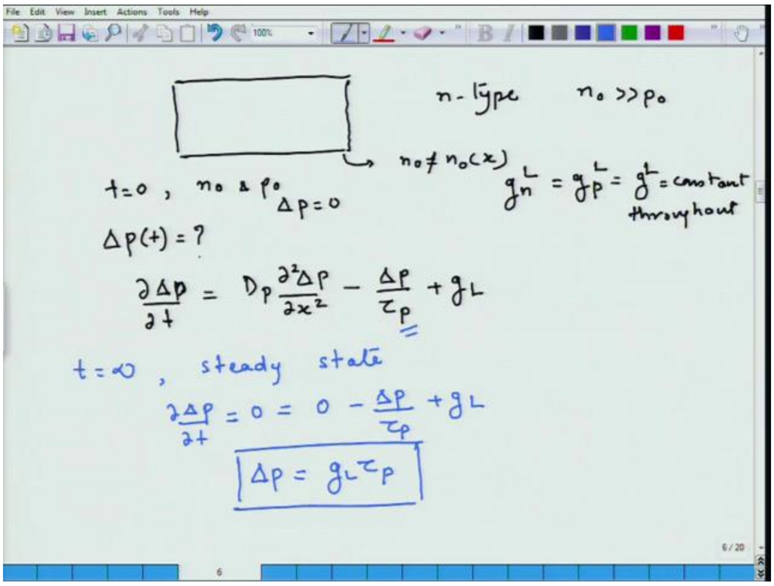

So, let me take a semiconductor and a semiconductor is such that it has. Let us, say let me define it as a n type semiconductor, which basically means its n 0 is much greater than p 0 the equilibrium concentration and since I am using the minority carrier diffusion minority. Carrier continuity equation it means there is no concentration gradient for n and p here. So, I can use that equation so n 0 is not a function of x so it is a uniformly doped semiconductor and then I find a way to generate.

Let us say, I am going to find a way to generate carriers and I am going to generate carriers in this material, which is by photo excitation such that. The electron generation is equal to hole generation and I can then write it as just g of L and I am doing it uniformly throughout the semiconductor. So, I am trying to remove the space variation in the generation so g L is generation rate, which is a constant throughout. So, this is a constant throughout and I want to see what will happen to the carrier concentrations where t is equal to 0.

The carrier concentration is n 0 and p naught and the material is majority n type. So, n 0 is much greater than p 0 and hence the minority carrier that we are worried about is delta p that is what we will be solving for and I want to find out that t is equal to 0 its n 0 and p 0 which basically means delta p is 0. So, there were no excess carriers in the material at t is equal to 0 I find a way to generate carriers. Let us, say photo excitation such that at every point I am generating carriers that are constant rate and which is given by g L and I want to find out how is delta p changing as a function of time.

This is what I want to find out and I am going to use the minority carrier continuity equation to do that. So, I will use the minority carrier continuity equation for excess carriers and this is for p here diffusion the excess carrier concentration for holes minus so this is a equation that I need to solve. So, let us first try to see what will happen in steady state so at t is equal to 0 we know delta p is equal to 0, but what will happen at t is equal to infinity.

So, first case is at t is equal to infinity so as I am shining light on the material it is generating more and more carriers delta p and delta n are increasing with time and when you generate excess carrier what will happen because of the recombination because of this term they will be recombining. So, eventually a time will come when the generation rate will be equal to the recombination rate at that point you are going to have a steady state carrier concentration in the material.

So, if I look at that situation in steady state t is equal to infinity in steady state basically I am saying this is going to be 0. So there is no change with time in steady state what is happening to the first term here. Since I am generating excess carrier at the same rate throughout the material, which has been shown here which means this term is also 0, which basically means I am left with concentration excess carrier concentration which means at t is equal to 0. The excess carrier concentration will be given by g L times tau of p.

So, this gives me what would be the eventual carrier concentration steady in a steady state in the material. If I am generating carriers by some means throughout the material at a uniform rate now if this is happening at steady state what is happening in between. So, what is happening from t to t infinity obviously we have gone from excess carrier being 0 to excess carrier being a steady state value.

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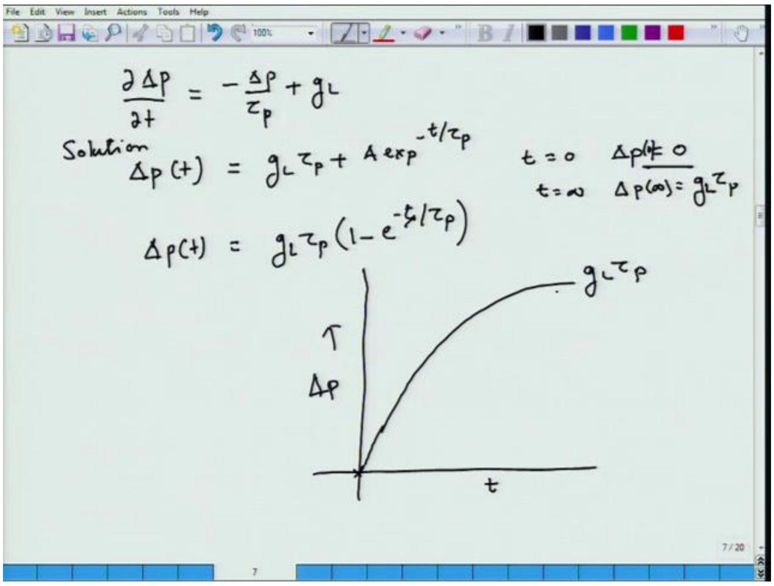

So, we need to look at what will happen in the, what is the transient phase? So if we look at the transient phase, then again we write the same equation, and see how we will solve it for the initial and final condition. So, which means the excess carrier concentration, the second term is still first term is a still 0 and the second term is given by... Now this is a well known differential equation, which have a solution, which is given by change in the solution for this equation will be of the form delta p as a function of time will be given by g of L tau p plus a exponential minus t over tau p and this if one solve for the initial condition.

At t is equal to 0 delta p is 0 delta p at 0 is 0 and at t is equal to infinity and we need only one value here to solve delta p at infinity is that. We have seen earlier g of l tau of p if we solve for this, which means delta p of t is changing and this will give us as expression for 1 minus exponential minus t over tau p. And if we try to plot what is happening in the system as a function of time t you can immediately see that if t is 0 what will happen if t is 0 then 1 minus 1 is 0 there are no carriers.

This is the condition here that at t is equal to 0 there are no carriers delta p is being plotted here and as t becomes very large this will increase as 1 minus of the exponential function. Eventually it will go to the value of g L of tau p and this is 1 minus of the exponential function it is going to change. So, this is consistent with what physically what we see by solving the minority equation. In the similar manner we will solve these continuity equations when we talk about devices and find a solution.

And at this point we will leave you with the final equations that need to be solved for any particular device, which are the in the general form these are the equations where you need to know what is the charge in your material? What is the field inside your device? What are the current densities? And when one solves all these equation one has taken into account all the carrier actions that are taking place in a semi conducting device. So, this is the starting of our discussion for the next module 4 where we will use these to look at what device characteristics look like, which basically means what is the current density as a function of voltage.

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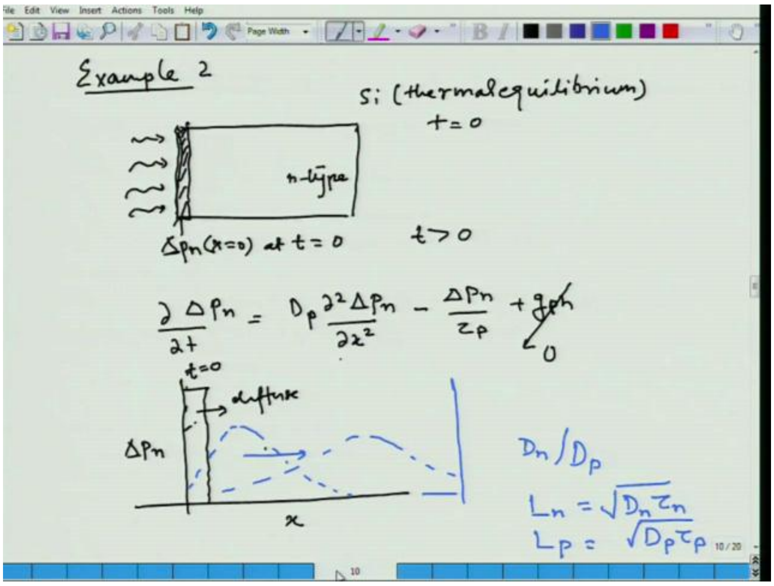

The second example for using minority carrier diffusion equation this is taken again. We assume a silicon semi conductor, which is in thermal equilibrium at t is equal to 0 at t is equal to thermal equilibrium and then I shine light at a edge at time t is equal to 0 and I am generating a carrier concentration at time t is equal to 0. I have generated let us say again this is a n type material and I have generated excess carrier concentration at x is equal to 0 by shining light on it at t is equal to 0 and then I stop shining light. So, what will happen to this carrier as it at time t greater than 0 this is what the question is.

So, the question is if I take a semi conductor I shine light on one end and I have a region up to which I will create carriers because of that rest of the bulk of the material do not have any carriers. And I want to figure out whatever excess carriers I have generated at time t is equal to 0 how will they diffuse into this material. So, again it is a problem of minority carrier diffusion and if we write that the minority carrier equation for this is going to be this is not going to be a steady state solution because this concentration of the carriers here is going to change with time.

So, we are looking for a transient solution plus. Now, since we had luminated this at time t is equal to 0 and then after that we shut off the light the photo generation for time t greater than 0 can be assumed to be 0. It is as if we created excess carriers and after that there is no photo generation in rest of the material. This part is going to be 0 this part will not be 0 because as you can see there is already a gradient there is much higher concentration of holes here compared to the rest of the material.

Hence, this gradient is going to exist and this term will of course, exist which is due to thermal gases and this is a solution that I am looking for in solving this particular problem. So, when one solves this problem one would see that it is basically being driven by the diffusion of the excess carriers into the semi conductors. And a solution for that can be obtained, which we have shown in one of the examples here and then that can be applied to our solution to find the delta p n.

If I plot the solution as a function of time in x the concentration of excess hole carrier initially at time t is equal to 0. I have a step function at time t is equal to 0 and as a time progresses. We will see this it is going to diffuse and the solution is going to be represented by a moving front, which is going diffusing as well as moving in this direction because of a electric field that is generated. So, this is what happens when we have a minority carrier diffusion equation and we try to apply it to certain situation.

Once, again this is a example which is used quite often because when we are trying to calculate the diffusion constant. Diffusion constant of the n or diffusion constant of the holes what is very important is the diffusion length for the n, which is given by square root of diffusion constant of the hole multiplied by the life time of the electrons or for holes. It will given by the diffusion constant for the holes multiplied by the life time of the holes and this is what will decide what will be the final distribution here.

So, I have shown in summary examples two examples, where we use the equation of a state or continuity equation a special case of it where we are applying it to the minority carrier diffusion in the devices. And two examples, in which how we use it and what are the solutions that we get; and these solutions then later will be used in the next module to look at the devices.