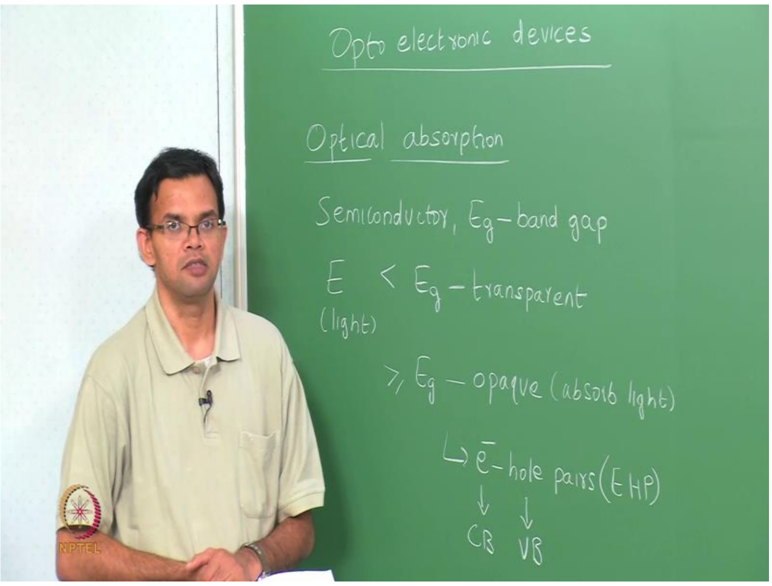
Electronic Materials, Devices and Fabrication
Prof. Dr. S. Parasuraman.
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Madras

Lecture No. - 15
Optoelectronic devices: Introduction

In the last few classes we have looked at electronic devices. So, we first started looking at a metal semiconductor contact forms your Schottky junction or Ohmic junction we then looked at p-n junctions and then finally, transistors we saw that there were different kinds of transistors. But we focused on the metal oxide semiconductor field effect transistors because, these are the once that are commonly used in your IC circuits. In the next few classes we are going to look at devices, where there is interaction of light with the electrical properties of the device.

(Refer Slide Time: 01:03)



So, we are going to look at optoelectronic devices. In these kinds of devices we have essentially two categories: 1 where you have an incident light which then create carriers in your material. So, a classic example of this is a solar cell were the incident solar radiation is absorbed in order to give you current. You also have the other type, where you inject electrons or hole into your device which then recombine in order to give you light.

So, this the example would be an LED a light emitting diode or a LASER. So, before we look into these devices let us first start by looking at interaction of light with matter. So, the first thing I going to look at is the phenomenal of optical absorption. So, we want to know what happens when light of certain energy is incident on a semiconductor. The case semiconductor, we define its energy by the band gap.

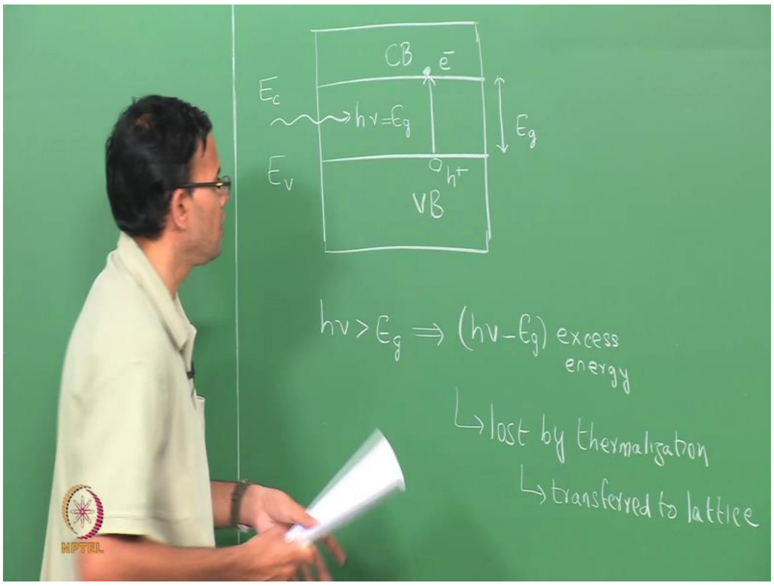
So, Eg which is the band gap of the semiconductor is nothing, but the energy difference between the valence band and the conduction band. We are going to say that your semiconductor is ideal. So that, there are no energy states between the band the valence band and the conduction band. So, in this particular case if you have light of certain energy incident on the semiconductor.

If E which is the energy of the light is less than Eg in the semiconductor set to be transparent off course, whenever you have interfaces you always have scattering. So, you could have scattering of light from the surface which semiconductor is and could have scattering from the various interfaces, but over all there is no optical absorption per say. In the other hand, if E is greater than Eg then we say that a semiconductor is opaque will essentially absorb the light.

So, when this thing happens when you have incident light of energy greater than Eg. And light gets absorb it produces electron hole pairs can also, abbreviate this as EHP which is means, electron hole pairs. So, you have electrons there are produce in the conduction band and holes that are produced in the valence band.

So, you have looked earlier at that concept of density of states and the Fermi function we found that at room temperature most of the electrons are located closed to the conduction band edge and most of the holes are located close to the valence band edge. So that, when you have your electron holes pairs being created they will essentially thermalize to the edges of the valence band and the conduction band.

(Refer Slide Time: 05:09)

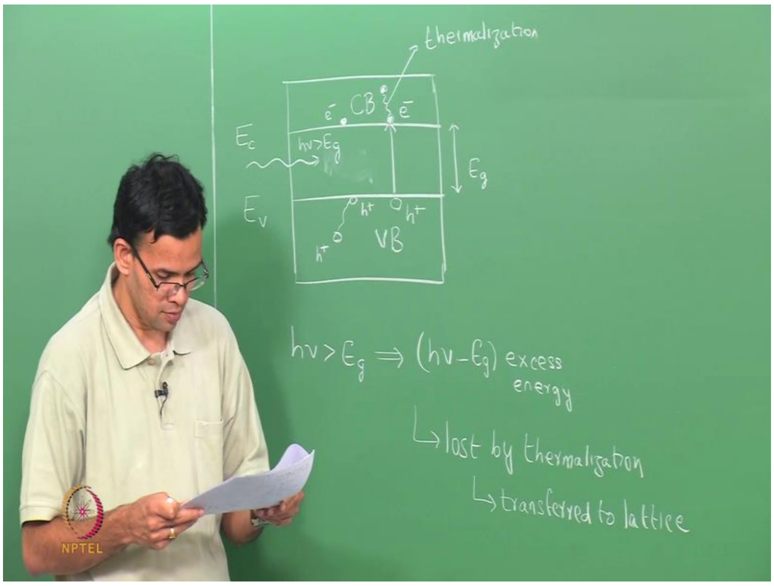


So, let me just explain this by drawing a small schematic. So, I have my semiconductor in which I mark a valence band and a conduction band Ev is your top of the valence band and Ec is the bottom of the conduction band so that, this gap is Eg. So, now we have light that is incident on the semiconductor the energy of the light is less than Eg then it is not going to be absorb.

So, if I have light of energy h mu when mu is the frequency equal to Eg or slightly above Eg is very close to the band gap. In this case an electron goes from the valence band to the conduction band so, let me show that here; an electron goes from the valence band to the conduction band in electron goes creates a hole. So, you have an electron at the bottom of the conduction band and a hole at the top of the valence band.

Now, if h mu is greater than which case light has in energy greater than the band gap there is some excess energy that is left. So, this excess energy can either be manifest in the electron in the conduction band or the hole in the valence band or both. But in this case, the electron or the hole looses this excess energy by process call Thermalization were the energy is lost to the lattice and then it goes to the edge of the valence and the conduction band.

(Refer Slide Time: 07:49)

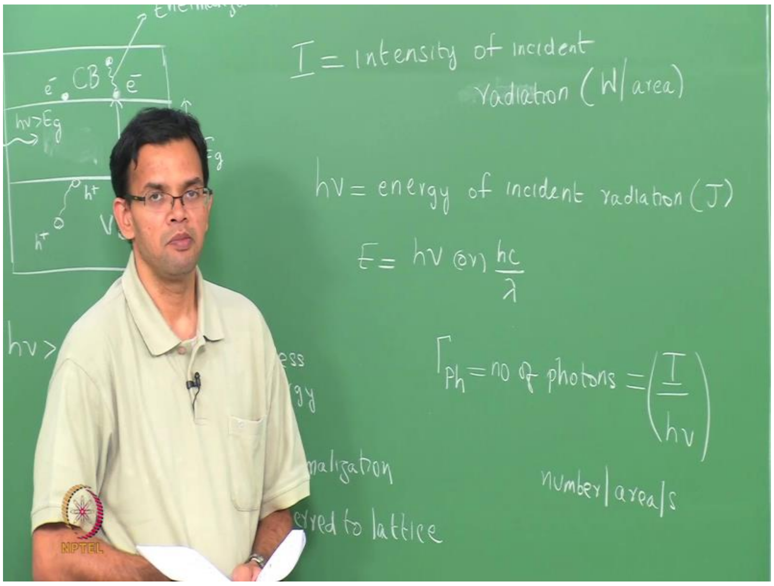


So, this excess energy is lost by thermalization and it is just transferred to the lattice. So, if I want to show that I will use the same diagram, but now I have h mu that is greater than Eg. So, in this particular case I can have a hole at the top of the valence band, but my electron can be somewhere within the conduction band. But this electron will lose energy and then ultimately come to the bottom of the conduction band.

So, you start with the hole at the top of the valence band because, h mu is greater that e g your electron goes not to the edge of the conduction band, but to some energy higher and the excess energy is lost by thermalization. You can also have a situation, where you have the electron at the edge of the conduction band and you have hole, where is deep within the material. And the hole looses energy and then goes to the edge of the valence band so, that is also possible.

So, the point is we have optical absorption whenever the energy the incident radiation is greater than or equal to Eg. Usually when h mu is just equal to Eg, you have the electron at the edge of both bands, but a density of states at the edge is 0. But we saw earlier then even if your kT above Eg, where kT at room temperature is just 25 mille electron Volts. We have large density of states. So, even for energies slightly above Eg and very close to it you will still have optical absorption.

(Refer Slide Time: 09:46)



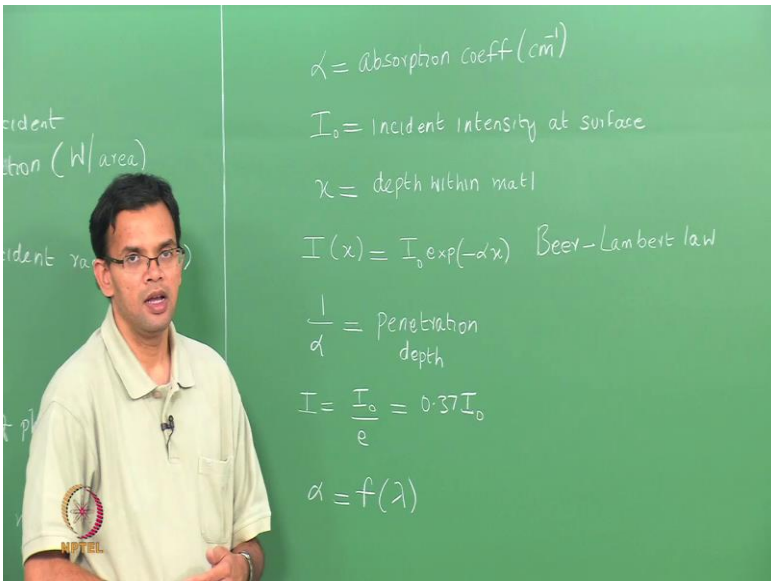
If I is the intensity of the incident radiation; I can given in units of Watts per unit area or watts per unit volume. So, this is let me say Watt per unit area this is nothing, but the power that is deliver to the sample and if h mu is the energy of the incident radiation mu nothing, but the frequency can also write energy as h mu or hc over lambda, where lambda is the wave length.

So, where you know the frequency or the wave length can find the energy. So, h mu is the energy of the incident radiation which is usually in Joules or electron Volts. Then, the number of photons that are incident on your sample at the surface so, ph is the number of photons which is incident at your sample is nothing, but I over the energy so, over h mu. So, this has the units of a number for unit area for unit time.

So, s is miss against area could be centimeter square or meter square, but it is the number of photons that are incident on your sample. Again if these photons have energy greater than the band gap they go into create your electron hole pads. So, this process can be 100 percent efficient means, every incident photon will generate 1 electron hole pad or the efficiency can less than 100.

So, we talk above the absorption of light by a material specially a semiconductor and we say that, light gets absorbed when the energy is greater than band gap. So, this we can quantify by introducing a term call the absorption coefficient.

(Refer Slide Time: 12:39)

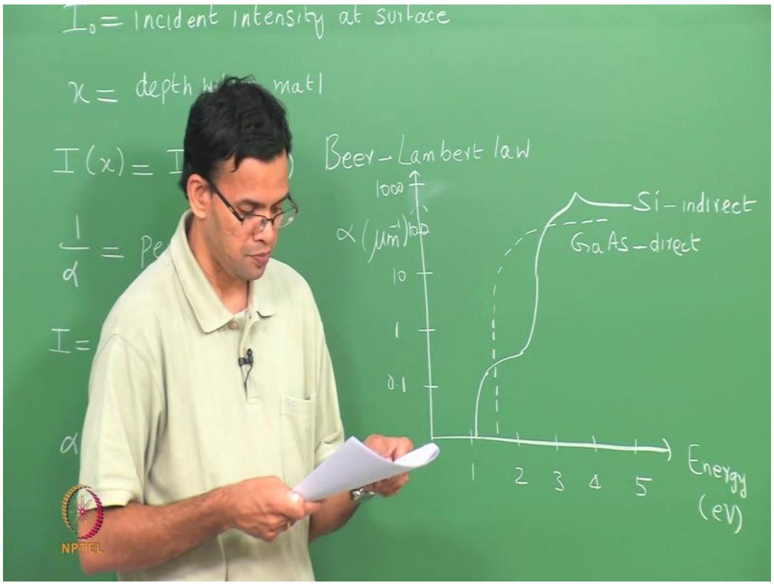


So we define a term alpha, where alphas call the absorption it has unit of centimeter inverse or length inverse. So, it could be centimeter inverse or meter inverse and so on. So, if alpha is the absorption coefficient and then I0 is the incident intensity at the surface and x is the depth within your material then the intensity I at some depth x is I0 exponential minus alpha x.

So, the intensity drops exponentially as you go deeper within your sample this is called Beer Lambert law. So, this is true whether you have incident radiation or visible light or uv or X rays in all of those cases you going to find, that the intensity goes down exponentially as you go within your sample. 1 over alpha which has a unit of length is call the penetration depth.

So, that at this distant I is nothing, but I0 over E which is 0.37 I0 which means, your intensity has dropped to 37 percent of the original intensity I0. We can relate this to the band gap of a material. So that, alpha is actually a function of the wave length of light. Because, wave length relates to energy and the energy can be compare to a band gap. So, we look at a semiconductor alpha is small if the energy is below Eg and then alpha becomes large once your energy exceeds the band gap.

(Refer Slide Time: 15:39)



So, we can show this web plotting the absorption coefficient as a function of energy. So, in this case I have alpha on my y access which is per micrometer and I am going to use a log scale a 0.1 1 10 100 let me just expand the scale of that 1000 on the x axis I am going to plot the energy of the radiation in electron Volts. So, 0 1 2 3 4 and 5 so, we will starts with Silicon.

So, Silicon is an indirect band gap material and its band gap is around 1.1 electron Volts at room temperature. So, below 1.1 your absorption coefficient is very small and then above 1.1 it starts to increase so, this here represents the band gap. So, it will have very low absorption below the band gap and very high absorption above it.

And do a similar plot for Gallium Arsenide, the difference between Silicon and Gallium Arsenide is that Silicon is an indirect band gap semiconductor. In this particular case you have seen earlier, if you want an electron transition from the valence band to the conduction band.

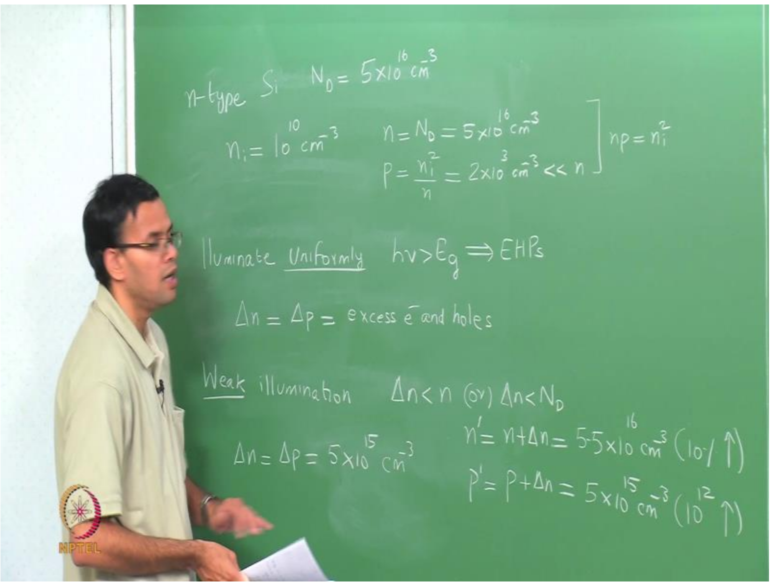
The transition needs some lattice vibration of phone ones to help it which is why you have a small increase initially when the energy is more when the band gap. To draw make a similar plot for Gallium Arsenide so; gallium arsenide is a direct band gap semiconductor with the band gap of 1.4.

So, initially when the energy is below 1.4the absorption coefficient is really small, but then it starts to increase rapidly once your energy is above the band gap. So, this is Gallium Arsenide so, this is a direct band gap semi conductor. So, that compare to silicon the rise in the absorption coefficient is really abrupt for Gallium Arsenide.

So, so far you have talked about absorption, but once your electron in hole pads are generated these are dynamic so, they tend to recombine. In the case of direct band gap semiconductor, when the electron in hole recombine the majority of the dominant mechanism by which energy is released is in the form of photons are light. So, those once the electron in hole recombines you get light whose wave length depends upon the band gap of the material.

So, in the case of Gallium Arsenide the energy of the light that comes out will be 1.43. In the case of Silicon which is an indirect band gap material the recombination takes place with the dominate mechanism be heat. So, that the energy is lost in the lattice has lattice vibrations. So, let us now look at some numbers where we have an electron hole pad being generated in a semiconductor due to incident light.

(Refer Slide Time: 19:53)



n-type Si $N_D = 5\times10^{16}\ cm^{-3}$

$n_i = 10^{10}\ cm^{-3}$ $n = N_D = 5\times10^{16}\ cm^{-3}$

$p = \frac{n_i^2}{n} = 2\times10^{3}\ cm^{-3} << n$ $\Big]\ np = n_i^2$

Illuminate Uniformly $h\nu > E_g \Rightarrow$ EHPs

$\Delta n = \Delta p =$ excess $\bar{e}$ and holes

Weak illumination $\Delta n < n$ (or) $\Delta n < N_D$

$\Delta n = \Delta p = 5\times10^{15}\ cm^{-3}$

$n' = n + \Delta n = 5.5\times10^{16}\ cm^{-3}$ (10% ↑)

$p' = p + \Delta n = 5\times10^{15}\ cm^{-3}$ (10^{12} ↑)

So, consider the case of an n-type semiconductor for simplicity a am just going to take the material to be silicon I have n-type silicon with my donor concentration equal to 5 times 10 to the 16 per centimeter cube. We will take the silicon to be at room temperature so that; the intrinsic carrier concentration is 10 to the 10. So, we have the semiconductor equilibrium we know that n is equal to ND which is 5 time 10 to the 16 P is just ni square over n.

If you do the numbers P is just 2 time 10 to the 3 which is much smaller than n. So, in this case we also know that np is ni scare your law of mass action is valid just how we calculated the concentration of P in the first place. So, in this n-type semiconductor i am going to illuminate it uniformly with light so that, I generate electron hole pads. So, I am going to illuminate uniformly.

So, when I say uniformly it means there have electron hole pad generated within the entire material, I am not varied about gradients within it later we will see what happens if we have gradients and the energy h mu is greater than Eg. So, that we have electron hole pads so, let delta n and delta p be the excess electrons and holes and these are equal because really you have an electron in a hole pad being created at the same time.

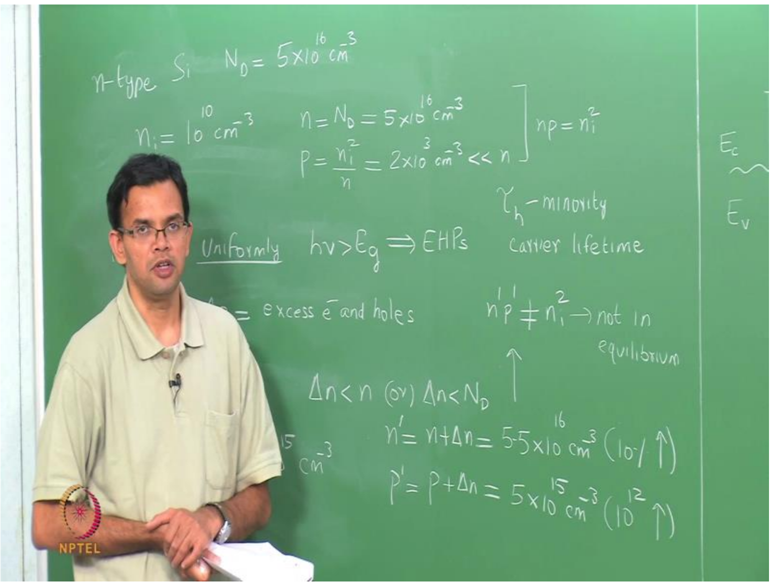
So, delta n and delta p are the excess we define a condition which we call Weak illumination in which case, the excess majority carriers which is electrons is less than the carrier concentration in the bulk of the material. So, the delta n is less than n or delta n is less than ND. So, in this particular example let us take delta n equal to delta p equal to 5 times 10 to the 15 per centimeter cube.

So, these are the excess in this number is less than ND. So, we have this your new electron concentration is let me called n prime which is the new is n plus delta n. So, n is 5 times 10 to the 16 the excess is 5 time 10 to the 15 to the new concentration is 5.5 times 10 to the 16 which is approximately at 10 percent increase.

On the other hand, your new hole concentration p prime is p plus delta n, but your p originally is very small is 2 times 10 to the 3 where the number of carriers you have generated is 10 to the 15. So, its p plus delta n which is the same as delta p so, it is equal to 5 times 10 to the 15 so, you have an increase by 12 orders of magnitude. So, the increase in the case of illuminate by light is always in the minority carriers.

So, this had been a p-type semiconductor the argument would have been reversed we find that there is a increase, in the amount of electrons a large increase in the amount of electrons compare to holes. So, that is increase is always in the minority carriers. When we turn off the light we have all of these excess carriers and when we have excess carriers.

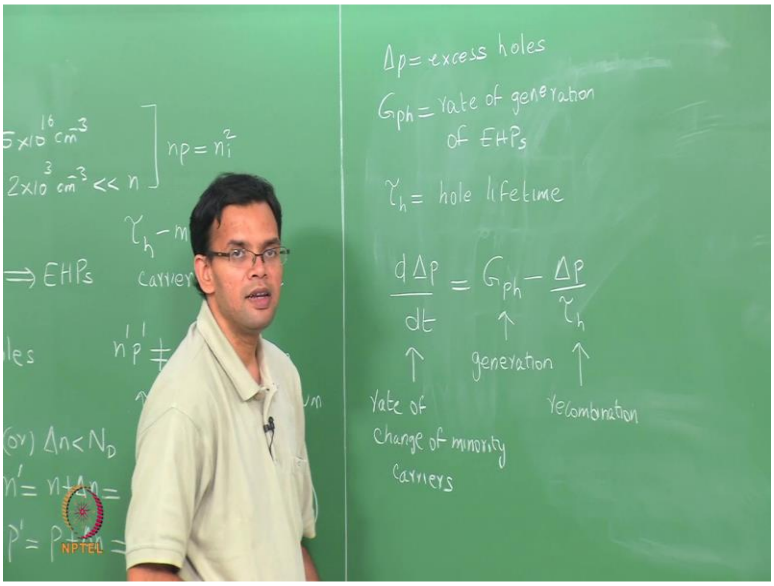
(Refer Slide Time: 25:26)



So, you will find that n prime p prime is not equal to ni square because, your system is not in equilibrium. So, now when I turn my light all these excess carriers have to start to recombine. So, the real increase in concentration is in that of the holes so, this recombination is driven by the lifetime of the holes. So, it’s driven by a quantity which we called tau h which is the minority carrier lifetime.

So, tau h determines how long does it for the electrons in holes to recombine so that, we go back to the equilibrium situation. So, this possible to right an equation were we link the excess carriers that are generated to the amount of electron hole pads are created and the amount there is lost to recombination.

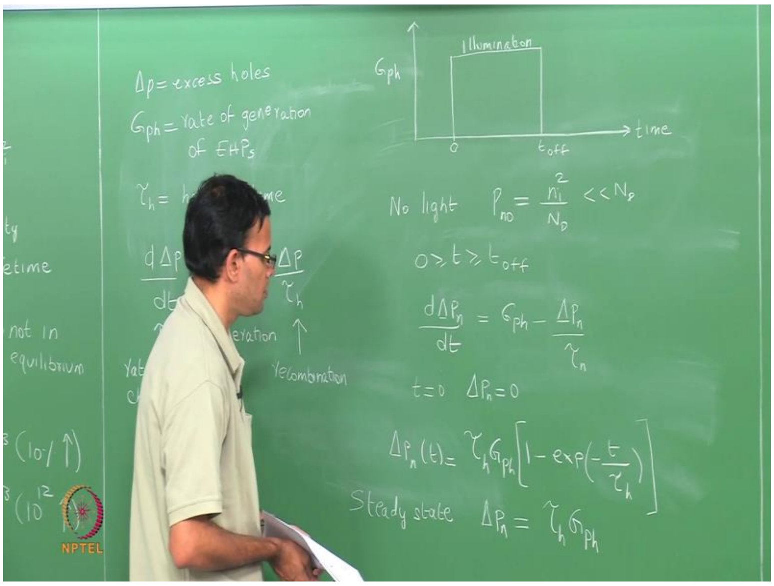
(Refer Slide Time: 26:47)



So, let delta p be the excess holes so, a still looking at an n-type semiconductor were if you looking at p-type then it will just be delta n. So, let delta p be the excess holes there are created and the Gph be the rate of generation of electron hole pads. We also define a minority lifetime tau h this is your whole lifetime.

So, we can write an equation that links d delta p over dt which is the rate of change of the minority carriers on the excess minority carriers, which is equal to how many that are generated minus how many holes there are lost due to recombination. So, this term is the rate of change of minority carriers; this 1 is the generation of new carriers, this 1 represents the recombination type. So, let us consider an example in order to understand this better.

(Refer Slide Time: 28:53)



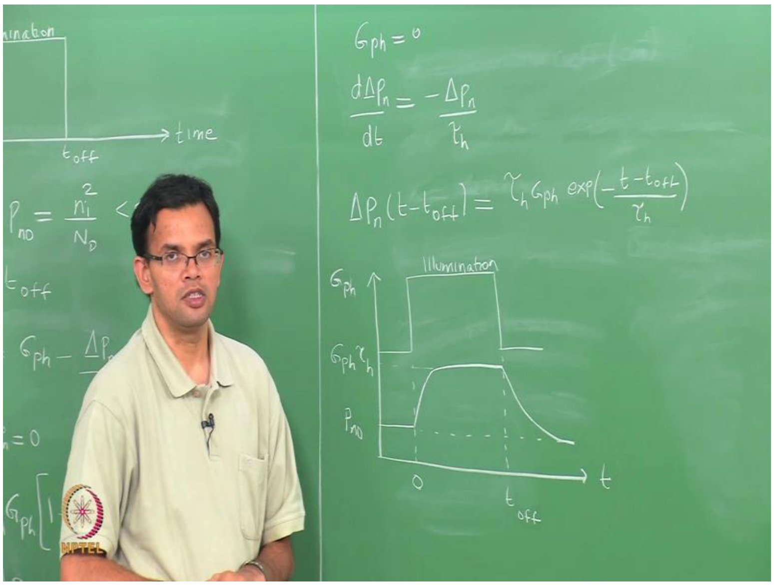
So, consider a case where i have a n-type semiconductor in equilibrium. So, this time in this excess i am shifting the 0 slightly to the right. So that, we can look at things more clearly so, you have a system that is at equilibrium at time equal to 0 we turn on the light. So that, we have some electron hole pads being created we let the light be on for some time. So, that the system achieve some study state and a time equal t off we turn off the light.

So, we have illumination within the so, the question we want to know is what happens to the minority carrier concentration in this process. So, when there is no light in usually p n not which is just the of holes in your n-type semiconductor is ni square over ND which is much smaller than n concentration ND. So, now I have the light being turned on so that, my time is greater than 0, but it is before to switched off so, it is before t off.

So, in this case I can write equation d delta Pn by dt so, I will just take this equation this is Gph minus delta Pn over tau n. So, this is just a first order differential equation we can integrated and the boundary condition is the time t equal to 0 delta Pn is 0 there are no excess carriers in your material. So, if I solve for this delta Pn a time t and this t is between 0 and t off is nothing, but tau h Gph 1 minus exponential minus t over tau h.

So, when the system is reach steady state your d Pn over dt is 0. So, at steady state the concentration of holes is nothing, but tau h Gph. So, now I am going to turn my light we will see what happens.

(Refer Slide Time: 32:37)

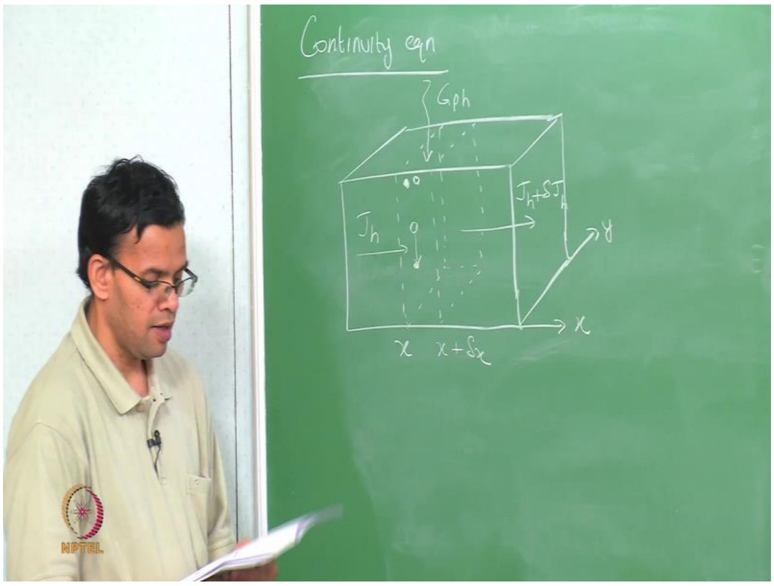


So, now, I am going to turn of the light so that, Gph is 0 there is no more generation of electrons or holes and the equation just reduces this again we can solve it is a first order differential equation. So, delta Pn so from t off so t off is when the light is turned off is nothing, but tau h Gph exponential minus t minus t off over tau h. So, this information we can put together and plot.

So, this is time so, we will first replot the light. So, we said that at time t equal to 0 we turn the light on and at time equal to t off. So, this is here illuminations this is Gph so, what happens to the concentration of the holes. So, initially your hole concentration is just p equilibrium concentration when you turn on the light the starts to increase and then it becomes a constant when you have steady sate this steady state value is Gph times tau h.

Then, when I turn the light off it decays exponentially until it reaches back the steady state. So far we have looked at the case of light interaction were you have a uniform illumination. So, it is possible to generalize this argument where we have a variation in concentration both along the depth of the material and also as a function of time. So, we call this the Continuity equation so let us, take a look at it next.

(Refer Slide Time: 35:19)

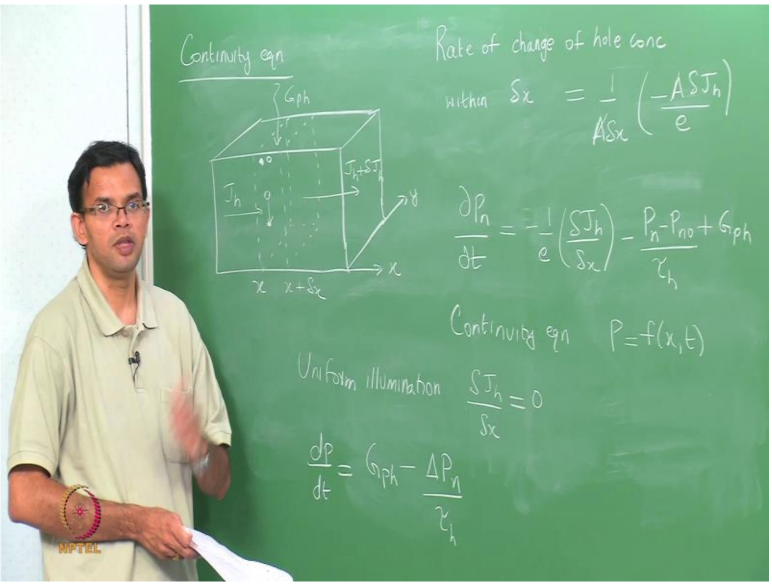


So, here we want to write a generalize equation for the interaction of the light with matter and how it generates electrons in holes. So, consider the case of a slab again for simplicity we are going to deal with an n-type material under weak illumination. So, that you ignore the changer in a majority carriers newly change significant change will be in a minority carriers.

So, I have a small portion of this material which is a certain depth edge and then I consider a small increment x plus delta x. So, this is just a portion of a its lab so, this direction is my x direction this direction is the y direction. So, I have some flux of holes there is entering into this small incremental slab at x. So, I am going to call it Jh which is the flux of holes where is entering the small portion and have a flux that is leaving want you call it Jh plus a delta Jh.

So, delta Jh can be positive or negative which pause to we have some generation of holes within the slab, if it is negative we have some loss of holes. We also have some incident light Gph, which creates electron hole pad and we also have a situation where we have recombination of electrons in holes. So, in this process generates new holes and the recombination basically is to loss of new holes.

(Refer Slide Time: 37:51)



So, in this particular case the rate of change of hole concentration within this portion delta x. So, rate of change of hole concentration within delta x. So, delta x is a small region of the slab is nothing, but 1 over a delta x. So, a is the area. So, that a delta is the volume minus a delta Jh over e. So, delta Jh is a change in flux as you go through the region so, a will essentially cancel.

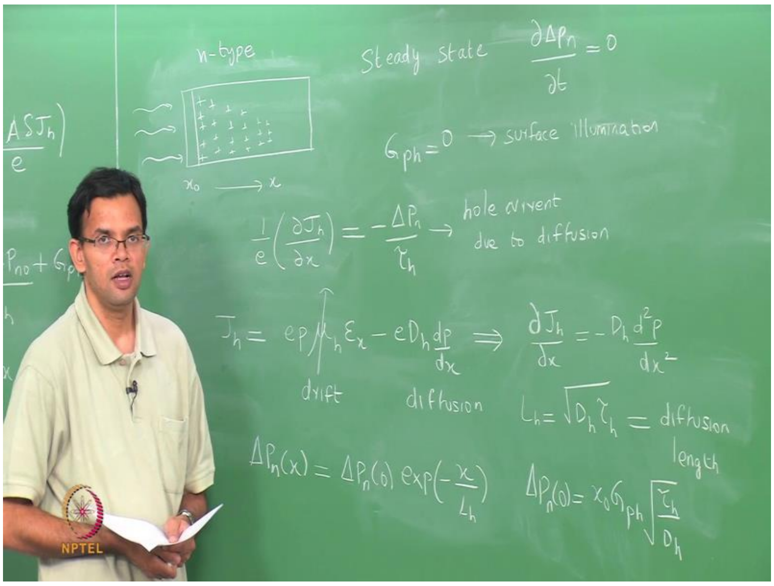
So, delta Jh according to this equation is negative, in this whole thing is positive there is an increase in the hole concentration. On the other hand, if it is positive is a decrease in the hole concentration. So, this just denotes the rate of change of hole concentration. So, we can relate this to how the concentration of holes actually change. So, d Pn or do Pn over do t is nothing, but minus 1 over e do Jh over do x.

So, it is just this term that is written here minus the holes that are loss to recombination. So, Pn minus Pn0 to the excess holes divided by tau h plus the holes that are generated which is Gph. So, this equation is called your Continuity equation. So, it is similar to a diffusion equation that you will write, in the case of diffusion of elements within see a metal or alloy in this particular case P is function of both x and time.

So that, the concentration of holes changes with time because it have generation and recombination and it also, changes with distance because you have some flux within the material. So, the continuity equation is a generalize equation when we think of say uniform illumination which we just saw before.

So, if you have uniform illumination in that particular case there is no flux within the material. So that, do Jh over do x 0. So, P will only change as a function of time. So, that you have dp over dt is Gph minus delta P over tau h. So, we get back the original equation that we wrote. So, uniform illumination is then just a specific case of the generalize continuity equation. So, let look at another case were instead of uniform illumination you just had illumination at the surface.

(Refer Slide Time: 41:54)



So, consider the case of a steady state continuity equation were I have an n-type semiconductor I have incident light only on the surface there is always going to be some absorption. So, I depict a small region of with x0 in which the light is absorbed. So, this is an n-type material we know that we are going to get some excess concentration of holes I am only showing the holes there also electron and these holes will essentially defuse within the material.

So, there are also electrons in here and I am only showing the minority carriers. So, you have light incident on the surface absorbed within some distance x0, which are creating your electron hole pads which then defuse to the materials. So, we are considering the system at steady state so that, do delta p and overdo t is 0 we also have a system of illumination only are the surface so, that Gph is 0.

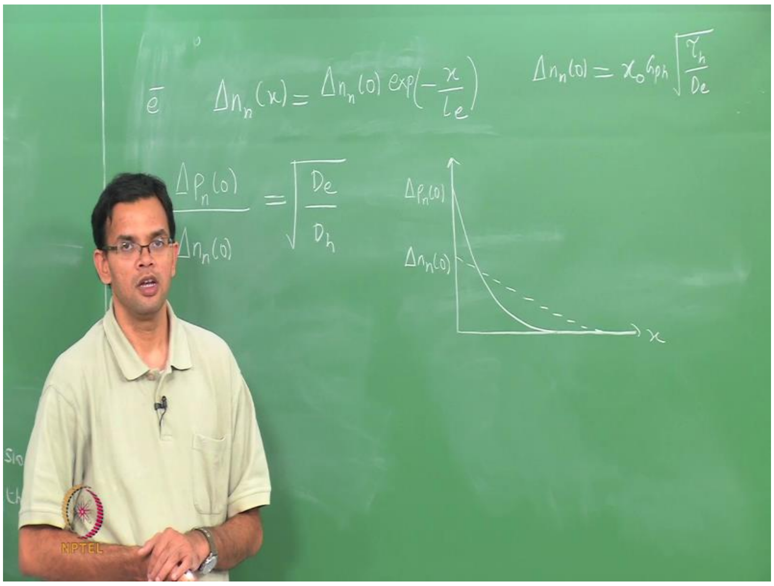
So, we can go back and rewrite the continuity equation in this particular case the equation simplified h over do x is minus delta Pn over tau h. So, you have a hole current that is set up mainly due to diffusion there is a generalize equation which relates the hole flux to both diffusion current and drift current with generalize equation Jh is ep mu h is epsilon x minus e Dh dp over dx.

So, the first term is due drift of the holes within an electric field, the second term is due to diffusion. If we ignore the drift current so that, this part we ignore we can equate this flux to this equation. So that, when we differentiate what we get do Jh over do x is minus Dh. So, in this particular case for weak illumination you can write an equation for the change for the change in the concentration of holes as we go along this length.

So, let me just mark this to be x so that, delta Pn is delta p n0 which is how many electron hole carriers there are generated at the surface times exponential minus x over l h. So, lh is call the diffusion length which is just diffusion coefficient times the x recombination time so, lh is the diffusion. So, delta Pn0 which is the number of carriers there are generated at the surface is equal to x0 Gph square root of tau h Dh.

So, it is related to how many carriers are generated within that region x0, where your light is absorbed. So, we can write a similar equation for the electrons and then we can plot how this carrier concentration goes as a function of distance.

(Refer Slide Time: 47:28)



So, for electrons we can write a similar equation this is den n of x which is your excess electron are generated not exponential minus x over Le, where Le is the diffusion length of the electrons. So, delta P n0 which is the number of holes generated are the surface by delta n n0 is nothing, but square root of De over Dh. So, delta n n0 is x0 Gph square root of tau h over De.

So, if you plot these excess concentrations as a function of distinct again in the case of majority carriers the change in concentration is not much. So, this is delta n n0 going as a distance within the material on the other hand for a minority carriers the slope is much more so, this is delta P n0. So, this is what happens when you have illumination at the surface you have electron in hole pad is generated which then diffuse within the material in order to give you a diffusion current.

So, today we have looked at some aspects of the interaction of light with the semiconductor material. So, starting next class we will start to look at some devices and example of where we can use this in the case electronic material.