Fundamentals of electronic materials, devices and fabrication

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Lecture - 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 an 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 ones 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. So, we are going to look at Optoelectronic devices.

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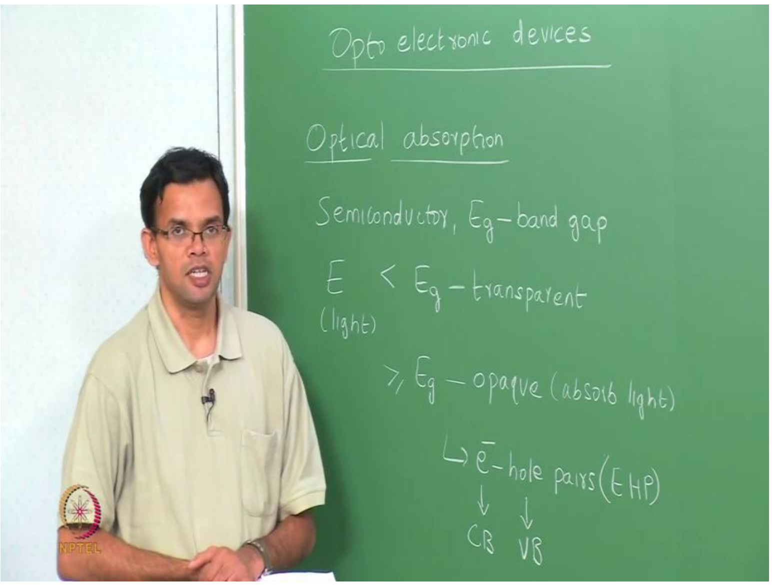

In these kinds of devices, we have essentially 2 categories, one where you have an incident light, which then create carriers in your material. So, a classic example of this is you are solar cell, where the incident solar radiation is absorbed in order to give you current. You also have the other type where you inject electrons or holes into your device, which then recombine in order to give you light. So, this 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 the interaction of light with matter. So, the first thing we are going to look at is the phenomenon of Optical absorption. So, we want to know what happens when light of a certain energy is incident on a semiconductor? In the case of Semiconductor, we define it is energy by the band gap. So, E g 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 you are semi conductor is ideal, so that there are no energy states between 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 E g then the semiconductor is set to be transparent. Of course, whenever you have interfaces you always have scattering. So, you could have scattering of light from the surface. A semiconductor is polycrystalline, you could have scattering from the various interfaces. But, over all there is no optical absorption percent, on the other hand if $E > E_g$ then we say that your semiconductor is opaque, it will essentially absorb the light. When this thing happens, when you have incident light of energy greater than E_g and light gets absorbed, it produces electron hole pairs, you can also abbreviates this as EHP just means a Electron Hole Pairs. So, you have electrons that are produced in the conduction band and holes that are produced in the valence band.

So, you have looked earlier, at the concept of density of states and the Fermi function. We found that at room temperature, most of the electrons are located close 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 whole pairs being created they will essentially thermalize to the edges of the valence band and the conduction band. So, let me just explain this by drawing a small schematic.

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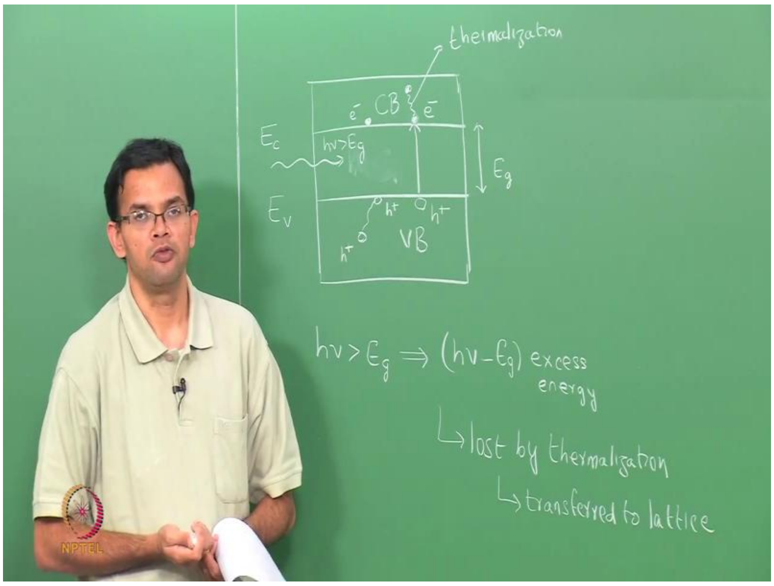

So, I have my semiconductor in which I mark a Valence band and a Conduction band, E_v is your top of the valence band and E_c is the bottom of the conduction band so that, this gap is E_g. So now, we have light that is incident on the semi conductor. The energy of the light is less than E_g then it is not going to be absorbed. So, if I have light of energy $h \upsilon$, where υ is the frequency equal to E_g or slightly above E_g 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, 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 $h\upsilon$ is greater than E_g, if $h\upsilon > E_g$ in which case light has 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 and 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 a process called Thermalization, where the energy is lost to the lattice and then it goes to the edge of the valence and the conduction band. So, this excess energy is lost by Thermalization that is, it is just transfer to the lattice. So, if I want to show that I will use this same diagram, but now I have $h\upsilon$ that is greater than E_g.

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 loose energy and then ultimately come to the bottom of the conduction band. So, you start with a whole at the top of the valence band because, $h\upsilon > E_g$. 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 a hole that 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 of the incident radiation is $\geq E_g$. Usually, when $h\upsilon = E_g$, you have the electron at the edge of both bands, but the densities of states at the edge is 0, but we saw earlier then even if your k T above E_g and k T at room temperature is just 25 milli electron volts, you have a large density of states. So, even for energies slightly above E_g and very close to it, we will still have Optical absorption.

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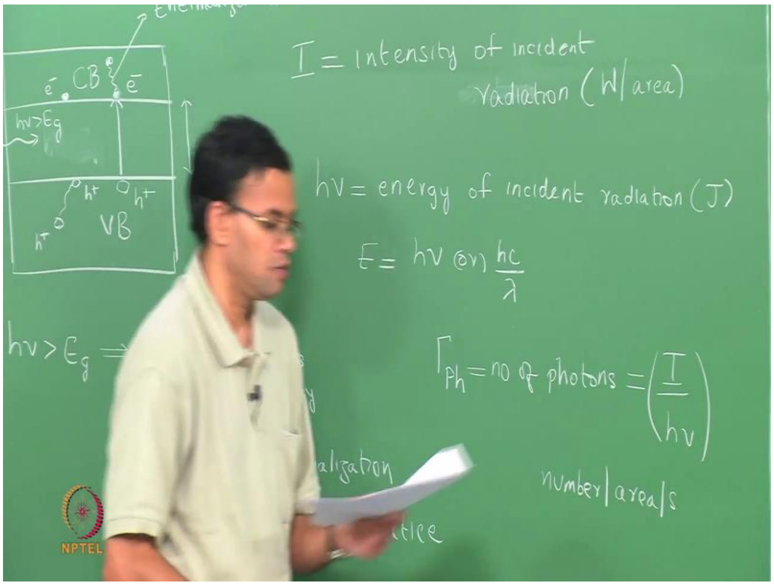

If I is the Intensity of the Incident radiation, I can be given in units of watts per unit area or watts per unit volume. So, this is let me say watt per unit area which is nothing but, the power that is deliver to the sample. And if $h\upsilon$ is the energy of the incident radiation υ is nothing but, the frequency. Then also write energy as $h\upsilon$ or $\frac{hc}{\lambda}$, where λ is the wavelength. So, whether you know the frequency or the wavelength, you can find the energy. So, $h\upsilon$ is the energy of the incident radiation, this 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, since incident at your sample is nothing but $\frac{I}{hc}$.

So, this has the units of a number per unit area, per unit times. So, s is in seconds, area could be cm^2 or m^2, but it is a number of photons that are incident on your sample. Again, if these photons have energy greater than the band gap, they are going to create your electron hole pairs. So, this process can be hundred percent efficient which means, every incident photon will generate 1 electron hole pair or the efficiency can be less than 100.

So, we talked 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 called the absorption coefficient.

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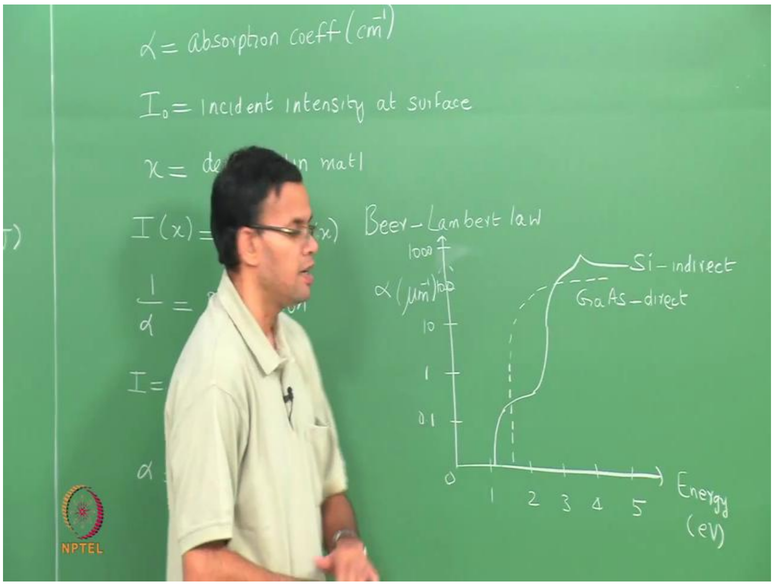

So, we define a term α. Where, α is called the absorption coefficient, it has units of cm^{-1} or length inverse. So, it could be cm^{-1} or m^{-1} and so on. So, if α is the absorption coefficient and then I_o is the Incident intensity at the surface and x is the depth within your material. Then the intensity I at sum depth x is $I_o \exp(-\alpha x)$. So, the intensity drops exponentially as you go deeper within your sample, this is called the Beer-Lambert law. So, this is true whether you have incident infra-red radiation or visible light or UV or X-rays, in all of those cases we are going to find that the intensity goes down exponentially as we go within your sample.

$\frac{1}{\alpha}$, which has a units of length is called the Penetration depth so that, at this distance I is nothing but, $\frac{I_o}{e}$ which is 0.37 I_o which means, your intensity has dropped to 37 percent of the original intensity I_o. We can relate this, to the band gap of a material. So that α is actually a function of the wavelength of light, because wavelength relates to energy and the energy can be compared to your band gap. So, if you look at a semiconductor α is small, if the energy is below E_g and then α becomes large once your energy exceeds the band gap. We can show this by plotting the absorption coefficient as a function of energy.

So, in this case I have α on a y axis, which is in per micro meter and I am going to use a log scale. So, I have 0.1, 10, 100 let me just expand this scale a bit 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 start with Silicon. So, Silicon is an indirect band gap material and it is 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 that, you have very low absorption below the band gap and very high absorption above it.

You can 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 or phonons to help it, which is why you have a small increase initially, when the energy is more than the band gap. Make a similar plot for Gallium Arsenide. So, Gallium Arsenide is a direct band gap semiconductor with a band of 1.4. So, initially when the energy is below 1.4 the 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 semiconductor. So, that compared to silicon the rise in the absorption coefficient is really abrupt for Gallium Arsenide.

So, so far we have talked about absorption, but once your electron in hole pairs are generated these are dynamic so they tend to recombine. In the case of a direct band gap semiconductor when the electron and hole recombine the majority of the dominant mechanism by which energy is released is in the form of photons or light. So, that once the electron and hole recombines, you get light whose wavelength 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 dominant mechanism being heat. So, that the energy is lost in the lattice as lattice vibrations. So, let us now look at some numbers where we have an electron hole pair being generated in a semiconductor due to incident light.

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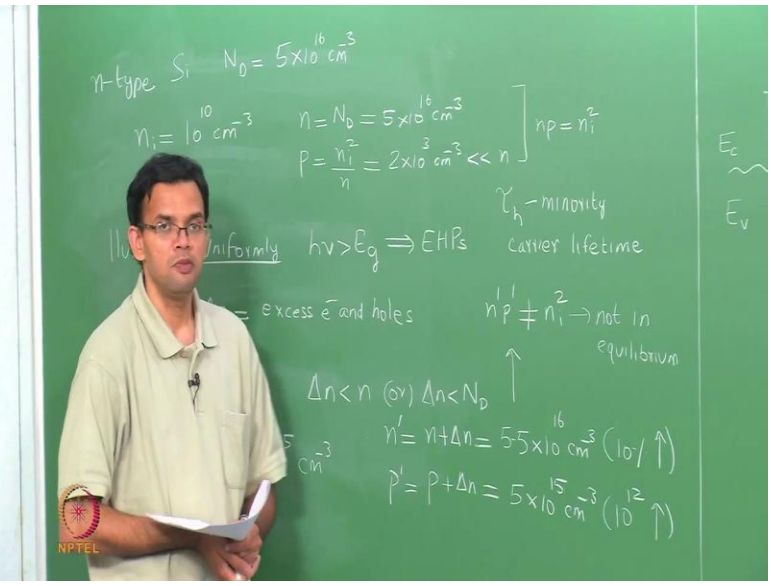

So, consider the case of an n-type semiconductor. For simplicity, I am just going to take the material to be Silicon; I have n-type silicon with my donor concentration equal to 5 x 10^{16} cm^{3} . We will take this silicon to be at room temperature, so that the intrinsic carrier concentration is 10^{10} . So, if you have the semiconductor at equilibrium we know that n is equal to N_D which is 5 x 10^{16}. p is just $\frac{n_i^2}{n}$ and if you do the numbers p is just 2 x 10^{3} which is much smaller than n. So, in this case we also know that n_p is n_i^2. Your law of mass action is valid, which is how we calculated the concentration of p in the first place.

So, in this n-type semiconductor I am going to Illuminate Uniformly, with light so that I generate electron hole pairs. So, I am going to Illuminate uniformly. So, when I say uniformly, it means that I have electron hole pairs generated within the entire material. I am not worried about gradiance within it. Later we will see what happens if you have gradiance. And the energy hυ is greater than E_g so that we have electron hole pairs. So, let Δn and Δp be the excess electrons and holes and these are equal because, really you have an electron in a hole pair being created at the same time. So, Δn and Δp are the excess.

We define a condition, which we call Week illumination, in which case the excess majority carriers which is electrons is less than the carrier concentration in the bulk of the material. So, that $\Delta n < n$ or $\Delta n < n_{ND}$. So, in this particular example let us take $\Delta n = \Delta p = 5 \text{ x } 10^{15} \text{ cm}^3$ so, these are the excess and this number is less than ND. So, if you have this, your new electron concentration is let me call it n prime, which is the new is $n + \Delta n$. So, n is $5 \text{ x } 10^{16}$, the excess is $5 \text{ x } 10^{15}$. So, the new concentration is $5.5 \text{ x } 10^{16}$, which is approximately a 10 % increase.

On the other hand, your new hole concentration p' is $p + \Delta n$, but your p originally is very small is $2 \text{ x } 10^3$ where the number of carriers you have generated is 10^{15}. So, it is $p + \Delta n$, which is the same as Δp. So, it is equal to $5 \text{ x } 10^{15}$ so you have an increase by 12 orders of magnitude. So, the increase in the case of illumination by light is always in the minority carriers. So, if this had been a p type semiconductor, the argument would have been reversed. We would 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 how 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 we will find that $n', p' \neq n_i^2$ because, your system is not in equilibrium. So, now when I turn off 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 is driven by a quantity which we call τ_h, which is the minority carrier lifetime. So, τ_h determines, how long does it take for the electrons and holes to recombine so that, we go back to the equilibrium situation. So, it is possible to write an equation where we link the excess carriers that are generated to the amount of electron hole pairs that are created in the amount that is lost to recombination.

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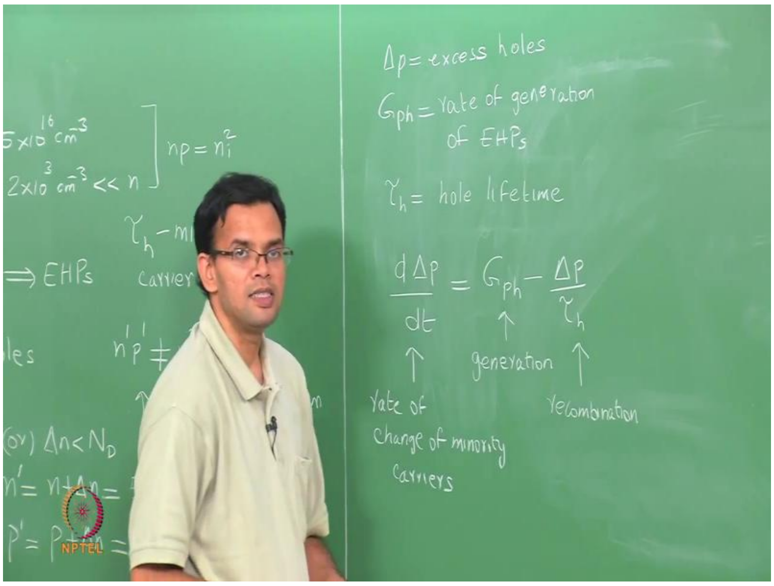

So, let Δp be the excess holes. So, we are still looking at an n-type semiconductor but, if you are looking a p-type then, it will just be Δn. So, let Δp be the excess holes that are created and let G_{ph} be the rate of generation of electron hole pairs. We also defined a minority lifetime τ_h, this is your hole lifetime. So, we can write an equation that links $\frac{d\Delta p}{dt}$, 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 that are lost due to recombination. So, this term is a rate of change of minority carriers, this one is the generation of new carriers and this one represents the recombination term.

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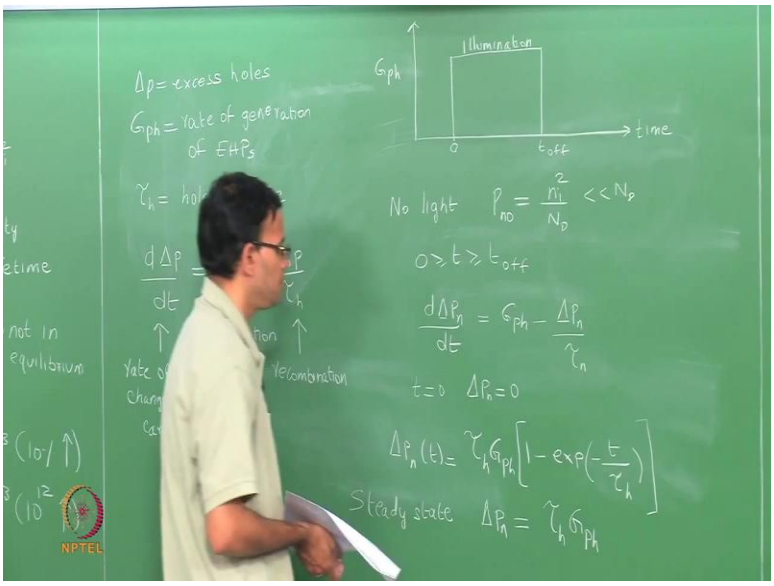

So, let us consider an example in order to understand this better. So, consider a case where I have a n-type semiconductor in equilibrium. So, this is time on this excess, I am shifting the 0, slightly to the right so that, we can look at things more clearly. So, you have a system that it is at equilibrium. At time equal to 0 we turn on the light so that, we have some electron hole pairs being created. We let the light be on for some time so that, the system achieves some steady state and a time equal to t_{off}, we turn off the light. So, you have illumination within this region.

So, the question we want to know is what happens to the minority carrier concentration in this process? So, when there is No light. Initially, P_{no}, which is just the concentration of holes in your n-type semiconductor is $\frac{n_i^2}{N_D}$, which is much smaller than N_D. So, now I have the light being turned on so that my time is greater than 0, but it is before it is switched off, so it is before t_{off}. So, in this case I can write this equation $\frac{d\Delta p_n}{dt}$. So, I will just take this equation, is $G_{ph} - \frac{\Delta p_n}{\tau_n}$.

So, this is just a first order differential equation, we can integrate it and the boundary condition is, at time t = 0 ΔP_n is 0. There are no excess carriers in your material. So, if I solve for this ΔP_n at time t and this t is between 0 and t_{off}, is nothing but, $\tau_h G_{ph}(1 - \exp(\frac{-t}{\tau_h}))$. So, when the system is reached steady state your $\frac{dp_n}{dt}$ is 0. So, at Steady state the concentration of holes is nothing, a $\tau_h G_{ph}$. So, now I am going to turn off my light, we will see what happens. So, now I am going to turn off the light.

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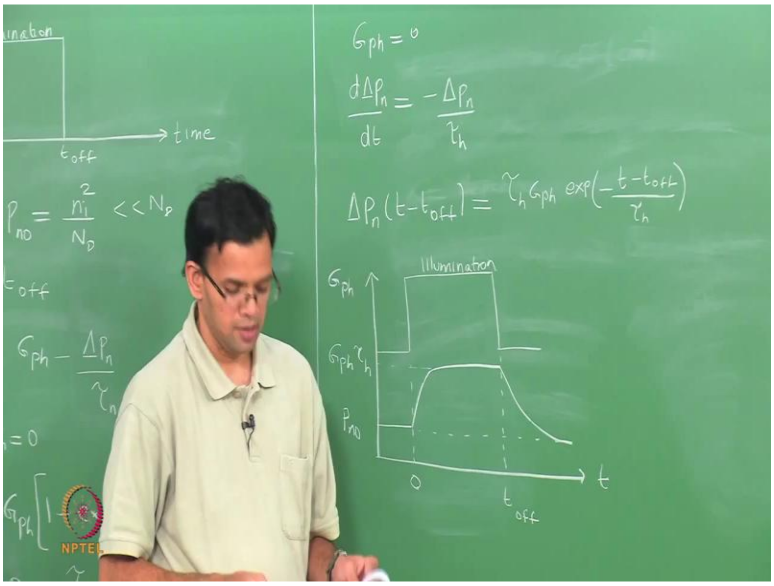

So, that G_{ph} is 0, there is no more generation of electrons or holes then, the equation just reduces. This again we can solve. It is a first order differential equation. So, ΔP_n so from t_{off}, so t_{off} is when the light is turned off is nothing but, $\tau_h G_{ph} \exp\left(\frac{-t-t_{off}}{\tau_h}\right)$. 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 turned the light on and at time equal to t_{off}. So, this is your illumination, this is G_{ph}. So, what happens to the concentration of the holes? Initially, your hole concentration is just the equilibrium concentration when you turn on the light, the concentrations starts to increase and then it becomes a constant when have steady state, this steady state value is $G_{ph} \times \tau_h$ and then when I turn the light off, it decades exponentially until it reaches back the steady state. So far we have looked at the case of light interaction, where 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.

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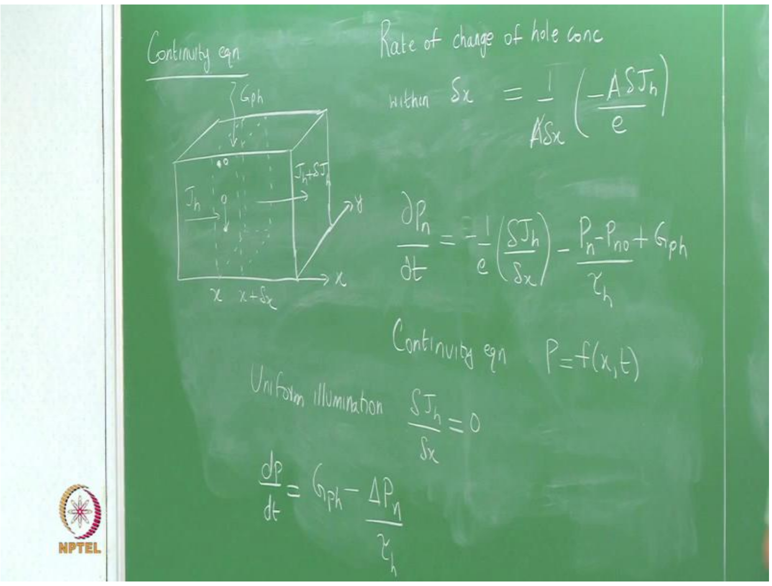

$$\text{within } \delta x = \frac{1}{A\delta x}\left(\frac{-A\delta J_h}{e}\right)$$

$$\frac{\partial p_n}{\partial t} = -\frac{1}{e}\left(\frac{\delta J_h}{\delta x}\right) - \frac{p_n - p_{no}}{\tau_h} + G_{ph}$$

$$P = f(x,t)$$

$$\frac{\delta J_h}{\delta x} = 0$$

$$\frac{dp}{dt} = G_{ph} - \frac{\Delta p_n}{\tau_h}$$

So, here we want to write a generalized equation for the interaction of the light with matter, and how it generates electrons and holes? So, consider the case of a slab. Again for simplicity, we are going to deal with an n-type material under week illumination so that, you can ignore the change in the majority carriers, you only change a significant change will be in the minority carriers. So, I have a small portion of this material which is at a certain depth x and then I consider a small increment $x + \Delta x$, so this is just a portion of you are slab. So, this direction is my x direction, this direction is the y direction.

So, I have some flux of holes that is entering in to the small incremental slab at x. So, I am going to call it J_h, which is the flux of holes that is entering this small portion and I have a flux that is leaving, I am going to call it $J_h + A\,\Delta J_h$. So, delta J_h can be positive or negative. If it is positive we have some generation of holes within this slab, if it is negative we have some loss of holes. We also have some incident light G_{ph}, which creates electron hole pairs 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. So, in this particular case the rate of change of hole concentration within this portion Δx. So, rate of change of hole concentration within Δx. So, Δx is a small region of the slab it is nothing but, $\frac{1}{A\Delta x.}$, so A is the area so that, $A\,\Delta x$. is the volume, $\frac{-A\Delta J_h}{e}$. So, ΔJ_h is a change in flux as you go through the region. So, A will essentially canceled.

So, if delta ΔJ_h according to this equation is negative then this whole thing is positive, there is a increase in the hole concentration. On the other hand, if it is positive there 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 concentrations of holes actually change. So, dP_n or $\frac{\tau_p}{\tau_t}$ is nothing but, $\frac{-1}{e}(\frac{\delta J_h}{\delta x})$, so it is just this term that is the written here, minus the holes that are lost due to recombination. So, $p_n - p_{no}$ which is your excess holes divided by τ_h + the holes that are generated which is G_{ph}. 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 a say a metal or an alloy. In this particular case p is a function of both x and time so that, the concentration of holes changes with time because we have generation and recombination and it also changes with distance because, you have some flux within the material. So, the continuity equation is a generalized 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, $\frac{\tau J_h}{\tau x}$ is 0. So, p will only change as a function of time. So, that you have $\frac{dp}{dt}$ is G_{ph} - $\frac{\Delta p}{\tau_h}$. So, we get back the original equation that we wrote. So, uniform illumination is then just a specific case of the generalized continuity equation.

So, let us look at another case, where instead uniform illumination you just have illumination at the surface.

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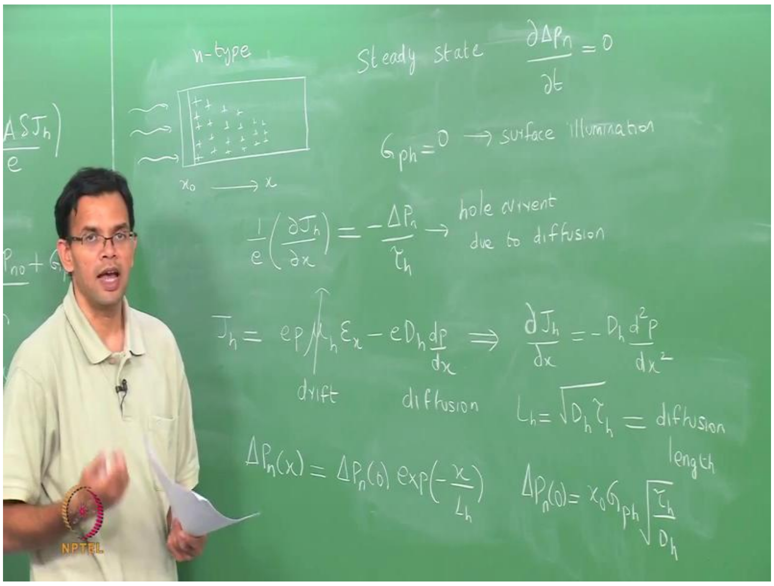

So, consider the case of a steady state continuity equation, where I have an n-type semiconductor. I have incident light only on the surface. There is always going to be some absorption so, I depict a small region of with x naught in which the light is absorbed. So if this is an n-type material, we know that we are going to get some excess concentration of holes, I am only showing the holes there are also electrons and these holes will essentially defuse within the material. So, there are also electrons in here, but I am only showing the minority carriers. So, you have light incident on the surface absorbed within some distance x_o which are creating your electron hole pairs, which then defuse through the material.

So, we are considering this system at steady state so that, $\frac{\tau \Delta p_n}{\tau_t}$ is 0. We also have a system of illumination only at the surface so that, G_{ph} is 0. So, we can go back and rewrite the continuity equation, in this particular case in the equation simplified $\frac{\Delta J_h}{\tau_x}$ is $\frac{-\Delta P_n}{\tau_n}$, $\frac{-\Delta P_n}{\tau_h}$. So, you have a hole current that is set up a mainly due to diffusion. There is a generalized equation, which relates the whole flux to both diffusion current and drift current, so that generalized equation J_h is $ep\mu_h \varepsilon_x - eD_h \frac{dp}{dx}$.

So, the first term is due to 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, $\frac{\delta J_h}{\delta x}$ is $-D_h$. So, in this particular case for Week illumination we 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 ΔP_n is ΔP_{no}, which is how many electron hole carriers that are generated at this surface times exp($\frac{-x}{L_h}$). So, L_h is called the diffusion length which is just the diffusion coefficient times the recombination time. So, L_h is the diffusion length. So, ΔP_{no} which is the number of carriers that are generated at the surface is equal to x_o G_{ph} $\sqrt{\frac{\tau_h}{D_h}}$. So, it is related to how many carriers are generated within the region x_o 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.

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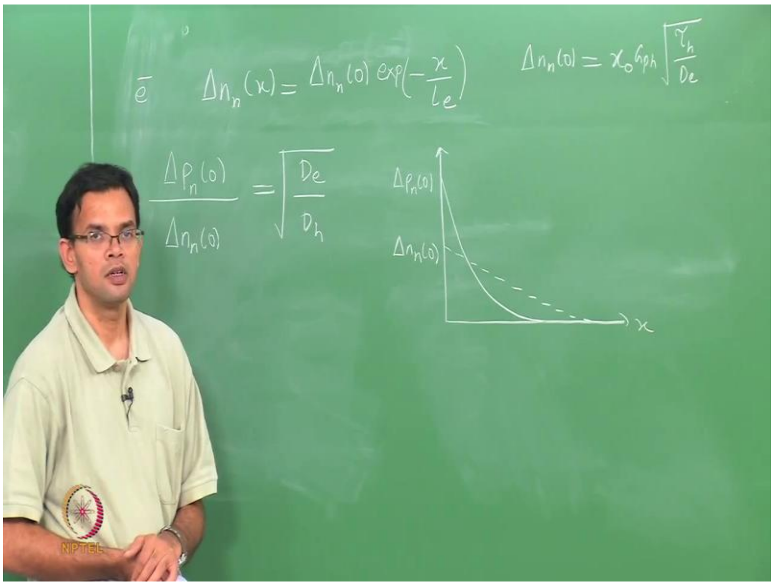

So, for electrons you can write a similar equation say $\Delta n(x)$, which is your excess electrons that are generated $\Delta n_n(o)\exp\,(\frac{-x}{L_e})$; where L_e is the diffusion length of the electrons. So, Δp_{no}, which is the number of holes generated at the surface by Δn_{no}, is nothing but $\sqrt{\frac{D_e}{D_h}}$. So, Δn_{no}delta n n naught it is $x_o G_{ph}\sqrt{\frac{\tau_h}{D_e}}$. So, if you plot these excess concentrations as a function of distance again in the case of majority carriers the change in concentration is not much, so this is Δn_{no} going as a distance within the material. On the other hand, for your minority carriers this slope is much more. So, this is Δp_{no}. So, this is what happens when you have illumination at the surface, you have electron in hole pair generated which then diffuse within the material in order to give you diffusion current.

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