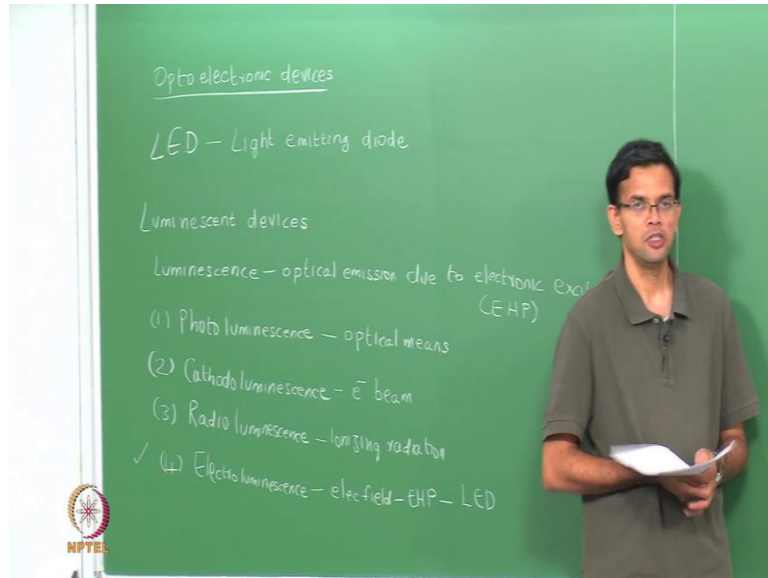


**Electronic Materials, Devices and Fabrication**  
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**Lecture - 22**  
**Optoelectronic Devices: LED's**

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So, in last class we mainly looked at the interaction of light with a semiconductor material. We said that if the energy of light is less than the band gap it will not get observed and if the energy is more than the band gap then the light can get observed, creating electron hole pairs. So, we were able to define an absorption coefficient that is wave length dependent.

Typically the absorption coefficient increases as the wave length goes down of the energy increases, but the actual value depends upon density of states of the material we also looked at the interaction of lights which say p type or n type semiconductor under conditions of weak elimination the increase in the concentration is highest for the minority carriers. So, if we had n type then increase in concentration is maximum for the p type or the whole. We also found that when shine light your  $n_p$  is not equal to  $n_i^2$  square your system is no longer in equilibrium. And when we turn the light off then the system goes back to equilibrium by the excess carrier recombining.

So, today we are going to start to look at optoelectronic devices. And the first device you are

going to focus on is the LED or the light emitting diode. If you remember there are mainly 2 kind of devices, those in which you have an injection of carriers that recombine in order to give you light. So, this could be in the visible region or in the infrared or UV.

You also have a case where you shine light on to a material and get in output in the form of electric current. So, LED's and lasers belong to the category of devices where by injecting carriers we produce light. Later we will look at a photo detector and the solar cell where the reverse process happens. So, LED's belong to the general category of luminescent devices. We can define luminescent as where we have optical radiation that is emitted because of electronic excitation.

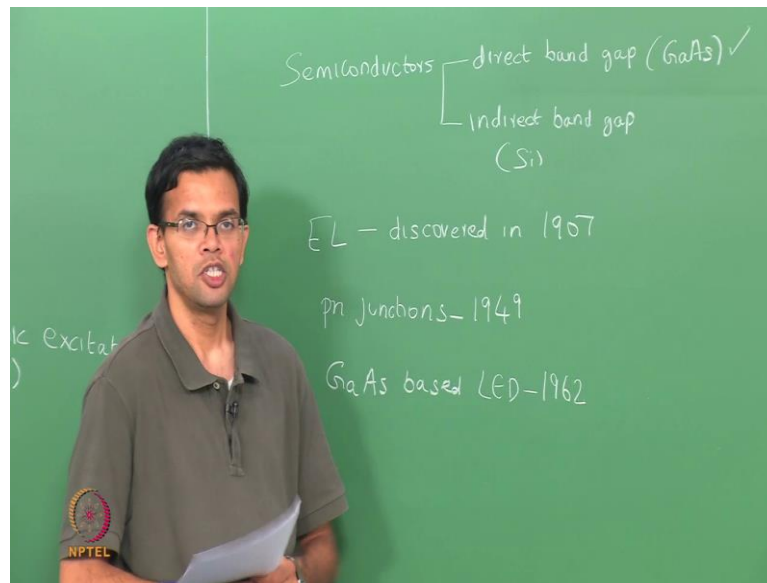
So, we will just write a working definition of luminescence is optical emission due to electronic excitation. So, in the case of semiconductors when we mean electronic excitation, we mean the creation of electron hole pairs. There are different ways of doing this electronic excitation, which leads a different kind of luminescence. In the case of photo luminescence, you use an optical means in order to create this excitation.

For example, if you have a material with a band gap in the visible region. You could shine light in the ultraviolet region which creates electron hole pairs. So, this creates the electronic excitation. When these electron holes recombine there will give light in the visible region. You can also have cathode luminescence, in which case you have an electron beam incident on your materials which creates the electron hole pairs. There is radio luminescence.

Here you use ionizing radiation ionizing. And finally, we have electro luminescence which is what an LED is in which case you use an electric field or an external field in order to create an electron hole pairs. So, electric field create the electron hole pairs and LED is an example of an electroluminescent device. So, we use the external field in order to create electron hole pairs. So, if you have p n junction, we typically inject the minority carriers.

These carriers can then recombine and we saw that depending upon the type of semiconductor, the recombination can either be dominated by photons or it can be dominated by heat.

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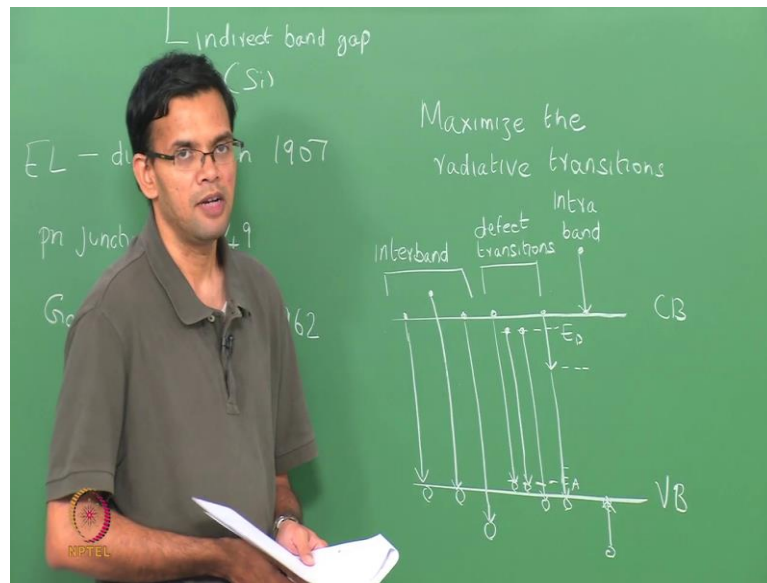


So, we have seen earlier semiconductors are essentially 2 types. So, you have your direct band gap and you have your indirect band gap. So, you seen that direct band gap semiconductor is one in which the electron hole recombination proceeds with the dominant mechanism, being the release of electromagnetic radiation or photons. In the case of an indirect band gap semiconductor the energy is released in the form of heat.

So, silicon is an example of indirect band gap semiconductor, gallium arsenide example for direct band gap semiconductor. In the case of an LED since we want a visible light to come out we preferentially use direct band gap semiconductors. So, the phenomenon of electro luminescence. So, I will just call it E L were first discovered in 1907, but until p n junctions were invented in 49 there was in much work done in this area.

So, p n junctions came in 1949 by the first LED based on gallium arsenide was only in 1960. So, what happens in the case of LED's, by means of injection we create these electron hole pairs. So, we have electrons in the conduction band and holes in the valence band. These electrons in holes can recombine and typically we want these recombination to give us light. Now there are different kinds of transitions there are possible. So, if you have general picture g.

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So, this is my conduction band this my valence band. So, the different ways in which the transitions can occur between the electrons and the holes. So, the first kind are called inter band transitions which can have electron in hole both are edge of the conduction band and valence band recombining. You can also have an electron deep in conduction band recombining with the hole the valence band edge or you can have electron in conduction band edge, recombining with the hole in the bulk of the valence band. So, all of these at the transitions occurs from the conduction band to the valence band is call your inter band transitions.

Now, if you have a material that is dope or as some other impurities, these basically cost defect states in the band gap. So, you could have for example, if you have a donor type impurity, that could lead to a donor level that is closed to the conduction band, could also have acceptor levels close to the valence band. These are essentially shallow states, if you have other impurity materials or other defects they could also forms states within slightly within the within the band gap.

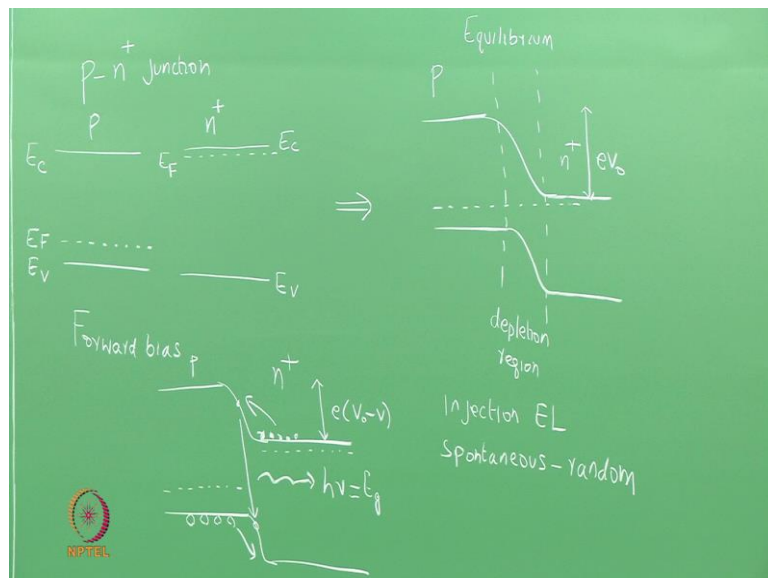
So, these are shallow states, this is a deep state. So, if you have electron hole pairs there are generated and these electrons in holes can get trapped in these defect states and then recombine those kind of transition are call defect transitions. So, I can have an electron in the conduction band recombining with the hole in an accepted states. So, I call this E which is my donor states E a is my accepted states I could have an electron in my donor state

recombining with the whole in the accepted state or I could have an electron in the donor state recombining with the accepted in the valence band.

And sometimes you can have transitions, where the electrons get trapped in deep states and then recombines with the hole. So, all of these transitions which involves some sort of defect states are called your defect transitions. You could also have transitions within the band these are called inter band transitions in this particular case you have an electron within the bulk of the conduction band and can go the edge of the conduction band. Similarly, you can have a hole in the bulk of the valence band which goes to the edge of valence band gap.

So, these are intra band transitions, not all of these transitions are radiative, only some of them are radiative. Will depend upon the band gap of the material and also upon the characteristic of these defect states. In the case of LED's we want to maximize the radiative transition. And minimize any non-radiative components in order to increase of efficiency of the device. For example, if you have defects then defects could act as straps. So, ideally we when you want an LED and when we be we process the materials we have to make sure know the defect states, that can basically cause non radiative recombination. The simplest kind of LED is essentially a p n junction based LED.

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So, let me start with that first. So, consider a simple p and plus junction. The n plus means that the n region is heavily doped. So, when we form a junction the depletion region is mostly within the p side. So, I have my p side E f, E v and E c this my p side and I have my n plus

region both my p and the n are the same material. So, the overall band gap is the same. So, now, I form a p n junction when this is at equilibrium, we know the fermi level line up. So, this the p that is the n plus. So, this the p n junction in equilibrium, we have a depletion region that mostly lies in the p side. And they also have built-in or a contact potential, we can forward bias the p n junction. In this particular case, if you forward bias junction.

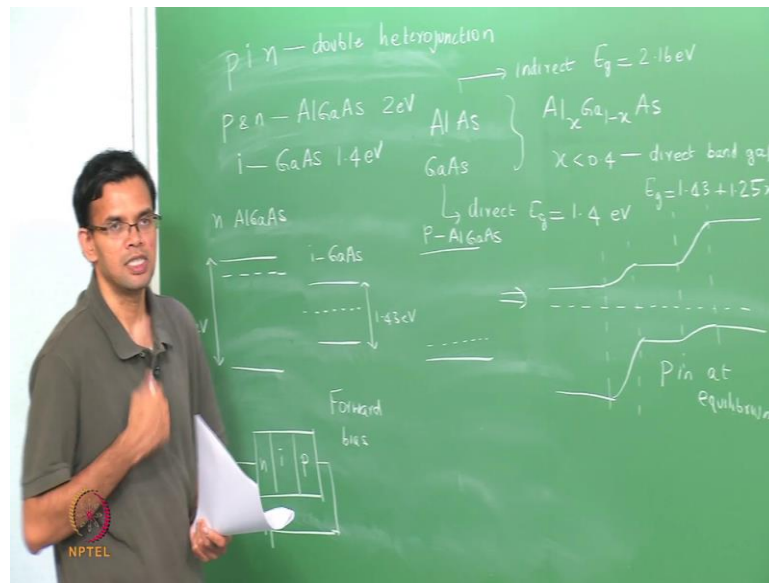
We would reduce the contact potential. So, that we inject the minority carriers on both sides. So, if you draw the band gap or band diagram of this in forward bias. So, you forward bias the p n junction. So, your new barrier is  $E_v - qV$ . So, when you forward bias we lower the barriers for the electrons in holes to go across.

These are the holes. So, these electrons in holes can recombine in depletion region. So, if you have an electron here and have a hole here, the electron in hole can recombine. If your material is a direct band gap material, then this recombination is dominantly produce light and the energy of the light is just given by the band gap. So, this is a case of a simple LED where we have just forward biased p n junction in order to produce light. So, this is an example of an injection electro luminescence because we inject carriers.

So, electrons in holes in order to generate your light. So, the formation of the light is essentially a spontaneous process. So, your electrons can holes and holes you can recombine not only in the depletion region. They can also recombine within the bulk of the material. So, the formation of light is a spontaneous process and it occurs randomly in all directions. Now, in the case of any device we always want to improve the efficiency of the device.

So, there is some way in which I can trap the carriers within the depletion region. So, that I have a majority of holes and electrons within this. And if it is a direct band gap material they I can improve the efficiency of device and also improve the amount of light output. In order to do this we modify the simple p n junction by introducing a hetero structure and we will see that we actually introduce 2 hetero structures in order to form a double hetero structure device. So, let us take a look at that next. So, we started off with the p n junction and we found that we want to maximize the electron in hole recombination within the depletion region.

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In order to do that we form a p i n. So, p is your p type i is an intrinsic and n is an n type and we make the materials different. So, that you have double heterojunction. So, let us consider an example for this consider a p and n type material that is made of aluminum gallium arsenide. And you have an intrinsic material that is made of gallium arsenide. Now, aluminum, gallium arsenide is actually composed of aluminum arsenide and gallium arsenide, which formula is usually given as  $Al_x Ga_{1-x} As$ . So, when x is equal to 1 is aluminum arsenide and 1 x is equal to 0 is gallium arsenide. Now, gallium arsenide is a direct band gap semiconductor with an  $E_g$  of 1.4 electron volts approximately is more like 1.42 or 1.43.

Aluminum arsenide is an indirect band gap semiconductor with  $E_g$  that is higher around 2.16. So, this is a direct band gap, this is an indirect band gap. This material can be a direct or an indirect band gap depending upon the value of x, for x less than 0.4 this is a direct band gap material and the band gap  $E_g$  is  $1.4325x$ . So, this is just an empirical relation. So, we start with aluminum gallium arsenide of band gap 2 electron volts. We have gallium arsenide band gap 1.4 electron volts.

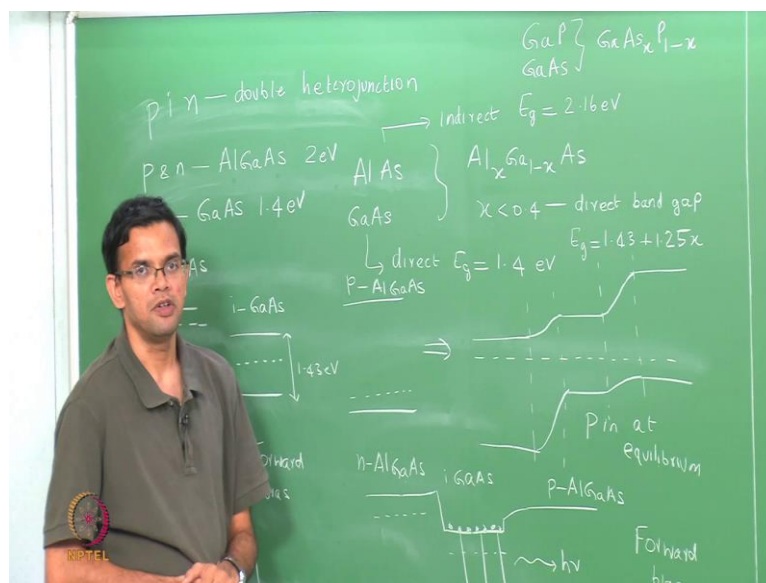
So, we going to form a double heterojunction with these 2 materials. So, let me first draw the energy band gap of these materials, when there for a part. And then when come together in order to form the junction. So, I have a my n type. So, I have my n alg aas. So, this band gap is 2 electron volts. We then have intrinsic gallium arsenide. You can either have an intrinsic

material or very lightly dope material. So, either way the band gap is smaller and the fermi level is close to the center of the gap. And then finally, I have p type gallium arsenide or p type aluminum gallium arsenide.

So, this intrinsic gallium arsenide is p type. So, now, we form a junction. So, we have 2 junctions and these are different materials. So, it is a heterojunction because we have 2 of these this forms a double heterojunction. So, once again at equilibrium the fermi levels must line up. So, that this is p i n at equilibrium most of the depletion region will be within the gallium arsenide. So, these are your 2 junctions, you essentially have 2 depletion regions. We then bias this p i n.

So, we bias this in such a way. So, n is connected to negative and p is connected to positive. So, in both cases we bias this junction in forward bias. So, this is an example of a forward bias. When we forward bias the n region is shifted up. And similarly the p region is shifted down. So, we can just take the example of 2 p n junctions and just shift them.

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When we do that so the bands bend up between the n region and the intrinsic and the bands bend down between the p region and the intrinsic. So, let me just mark. So, this is n – alg aas there is my intrinsic gallium arsenide that is p – alg aas. So, this is the case of the band diagram, when the junction is in forward bias. So, we are injecting the electrons from the n side and we are injecting the holes from the p side. Now, because of difference in band gaps we create this potential wells. So, we have a potential well were electrons can accumulate in



gallium arsenide. You also have a potential well in the valence band side. So, holes can accumulate these electrons in holes can recombine and then give you light. So, the energy of the radiation that comes out, depends upon the band gap of the gallium arsenide region. So, it as a value of around 1.4, but by using a double heterojunction we can make sure that most of the carriers are located in the intrinsic region.

So, that we increase the efficiency of the recombination and then produce more light. We can repeat this in other material, for example, instead of aluminum gallium arsenide, where the aluminum actually substitute for gallium. You can have another material where we have gallium arsenide in phosphide. So, that instead of substituting in gallium the phosphorus substitutes for arsenic. So, this is formed by combining gallium phosphide gap and gallium arsenide. So, I can have gallium phosphide and gallium arsenide. So, gallium phosphide is an indirect band gap semiconductor gallium arsenide is direct. So, this gives you gallium.

Again depending upon the value of the x, you can have a direct or an indirect band gap material. So, once again using this you can form a double heterojunction with gallium arsenide. Even there the energy of radiation that is comes out will be equal to the band gap of gallium arsenide.

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Transitions from CB  $\rightarrow$  VB  $\rightarrow$  thermal excitation  
 $\rightarrow$  broadening of the intensity  $\rightarrow$  line width ( $\Delta\lambda$ )


$e^-$   $h^+$

$$h\nu = \text{photon energy} = \left( E_c + \frac{\hbar^2 k^2}{2m_e^*} \right) - \left( E_v - \frac{\hbar^2 k^2}{2m_h^*} \right) = E_g + \frac{\hbar^2 k^2}{2m_\gamma^*}$$
 Joint dispersion relation

$\frac{1}{m_\gamma^*} = \frac{1}{m_e^*} + \frac{1}{m_h^*}$  Reduced effective mass

$P(E) = \exp\left(-\frac{E}{kT}\right)$  Boltzmann approximation

Joint DOS 
$$g_J(E) = \frac{4\pi(2m_\gamma^*)^{3/2}}{h^3} \sqrt{E - E_g}$$



In the case of an LED, transition occur from the valence band from the conduction band to the valence band the most of the electrons and holes are located at the edges of the conduction band and the valence band, but any given temperature there will always be sim

thermal excitation which means that will always have some broadening of the peak.

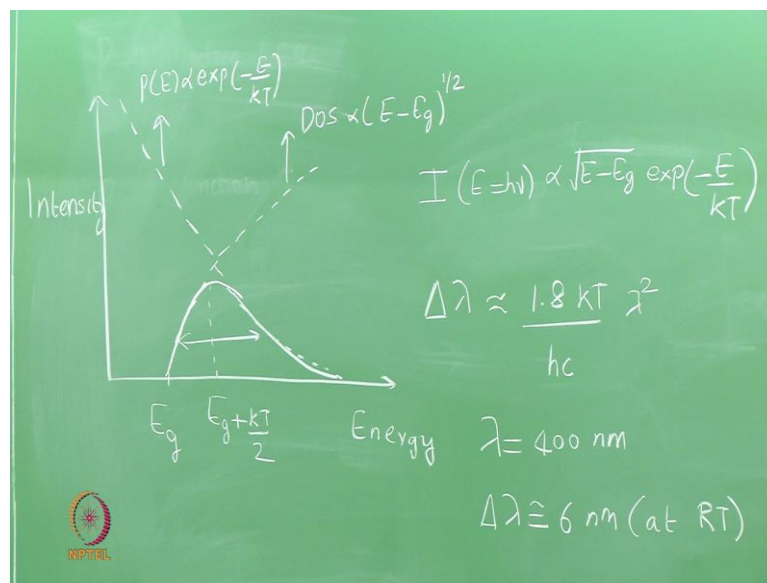
That come of the radiation that comes out we always be some thermal excitations this leads to a broadening of the intensity. So, that there is some line width. So, the line width depends upon the number of states that are available for the electron in the hole to occupy that is your density of states in also the probability of the occupation. So, that is your fermi function.

So, is the energy of photon and this is because of recombination of an electron in the conduction band which somewhere with the hole in the valence band having some other wave vector  $k$ . In the photon energy is nothing but  $E_c + \frac{\hbar^2 k^2}{2m_e}$  this represent the energy of the electron minus the energy of the hole  $E_v - \frac{\hbar^2 k^2}{2m_h}$ . So, this is the energy of the electron is the energy of hole.

So, these values of  $k$  can be different, but first simplicity let me just take them to be same. In this case this equation simplifies to  $E_g + \frac{\hbar^2 k^2}{2m_r}$ . So, this equation is call the joint dispersion relation,  $m_r$  is call the reduced effective mass an  $\frac{1}{m_r}$  is call the reduced effective mass.

You can similarly define a joint density of states. So, again if you assume a solid with the uniform potential then the joint density of states is  $4\pi^2 m_r$  we also need the occupation probability. You can assume that the occupation is a simple Boltzmann function. So, that  $p$  of  $e$  is just exponential minus  $e$  over  $k t$ . So, this is Boltzmann approximation. So, the line width which is the spread of the light that comes out from the LED because of thermal excitation, depends upon the density of states and the probability of occupation. So, we can show this in a graphical fashion.

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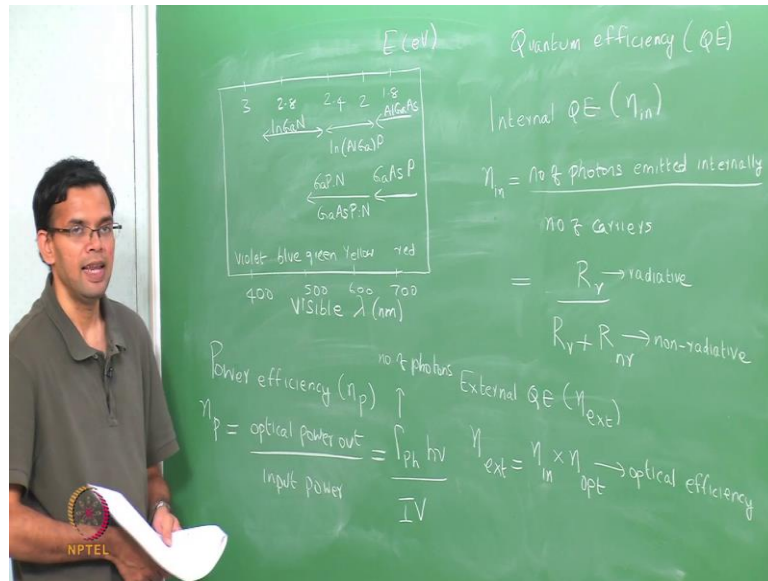


So, let me Plot the intensity verses the energy, y axis I have intensity x axis I have energy. Now, we would not have any light was energy is less than  $E_g$  because you cannot have any states in the gap. Minimum energy is  $E_g$ , now the density of states function increases as square root of the energy. So, this a density of states proportional to  $e$  minus  $E_g$  square root then we have the occupation probability. We said that goes as a Boltzmann function, which means as the energy increases the occupation probability decreases. This is  $p_f e$  proportional exponential  $e$  minus  $k t$ . So, the theoretical spectrum depends upon the product of these 2.

So, that  $I$  of some energy equal to  $h \nu$ , proportional to square root of  $e$  minus  $E_g$  exponential minus  $e$  over  $k t$ . So, plot this, this will be the spectrum of the intensity the  $p$  usually lies  $k t$  over 2 above  $E_g$ . And then there is a line width, this line width  $\Delta \lambda$  is approximately  $1.8 k t$  over  $h c \lambda^2$ . So, for example, if you have an LED which gives light at 400 nanometers. So, 400 nanometers is in the visible region in calculate  $\Delta \lambda$  it is just by a substituting this here.

And we take temperature to be room temperature  $\Delta \lambda$  is approximately 6 nanometers at room temperature. So, if you have different LED materials we can basically have light of different wave lengths. The wave length is going to depend upon the band gap of the LED material. So, we can summarize this in the form of a plot. So, I just like to look at the different LED materials.

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So, I will plot the visible region wavelength form of nanometers this is 400 500. We also plot the energy, energy is in electron volts somewhere around 3, 2.8, 2.4, 2.8. So, depending upon which region in the spectrum you want, we choose the corresponding LED material. We already saw that if you had gallium arsenide then gallium arsenide with a band gap of 1.4 actually gives a light in the i r region. So, within the blue region. So, if just were to mark this violet, blue, green, yellow and then red.

So, within the blue region typically you can use an indium gallium arsenide, indium gallium nitride based material for a slightly lower band gap. You have indium based with the aluminum gallium phosphide. So, it is an indium phosphide doped with aluminum and gallium. Already saw al gaas that as an energy around 2 electron volts depending upon the value of x. You also have gallium phosphide based materials, this gallium then you have.

So, if you see most of these materials are based upon 3, 5 you can also have 2, 6 based materials with different values, but their all based of gallium arsenide. So, gallium arsenide is a direct band gap material. And you can also you it as a substrate for growing many of these LED's. In order to avoid defects these LED's are usually grown by some means like chemical deposition or atomic deposition or even a simple physical vapour deposition like sputtering or laser processes.

So, this enable to growth different layers with minimum defects. Again you to choose your materials in such a way, but there is a lattes match. So, that if there is any lattes mismatch that

can also lead to defects. When we talk about LED's, we usually talk about the factor called a quantum efficiency, going to abbreviate this Q E. Now, there are different matrix for the quantum efficiency. First one is called the internal quantum efficiency and going to denote this is  $\eta_{in}$ . So, this the number of photons generated internally divided by total number of carriers. So,  $\eta_{in}$  is a number of photons emitted or generate internally divided by the number of carriers. So, this is nothing but the ratio of the recombination rate which is radiate to the total recombination. So,  $R_r$  which is the radiative recombination rate divided by the total. So, this radiative, this is non radiative. For a highly efficient device we want the internal quantum efficiency to be high, which means the radiative recombination rate must be much higher than the non-radiative part.

You can also define an external quantum efficiency. This is nothing but the number of photons emitted externally divided by the number of carriers. So,  $\eta_{external}$  depends upon the internal quantum efficiency times the optical efficiency of the device. This is related to the define device geometry, the reflectivity or the absorbance or a transmission of the various layers and so on. We also defines something called a power efficiency,  $\eta_p$  which will be optical power output divided by the input power. So,  $\eta_p$  is the optical power out divided by the input power.

The optical power output is nothing but the number of photons. So, this is number of photons times the energy  $h\nu$  divided by the input power which usually just  $I V$ . So, for we have looked at LED materials that are mainly based upon semiconductors you can also have LED based upon organic materials these are called o LED's. So, we will not talk much about them here because we mainly deal with inorganic semiconductor materials, but o LED's or o LED's also work on a similar principle.

In this case you have an inorganic materials which is your active materials sandwiched between 2 electros carriers are injected into this organic materials, which then recombine to give you light. So, usually o LED's because your organic materials, we do not talk about valence band or a conduction band, but we talk about molecular orbitals. So, we have something called a highest occupied molecular orbitals which is similar to a valence band and a lowest unoccupied molecular orbitals which is similar to your conduction band.

So, that when electrons holes recombining against this, you will get light. So, there are different o LED materials are available. Again you choose the material based upon the region

of wave length which were interested in. So, o LED's are useful mainly for display devices. They can easily be a thermally evaporated on to a substrate, but one of the problems with o LED is of course, the cost that is involved and the lifespan of these organic materials, stability of the organic materials is another issues. So, water damage is an issue there, but o LED are again another type of LED's which are based upon organic materials.

So, today we have looked of LED's. The next class we will focus on lasers. So, laser work on a similar principle to LED's, but there are some important differences, because we also need to create population inverses in lasers. So, we looked at lasers in the next class.