Fundamentals of electronic materials, devices and fabrication
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Lecture - 16
Optoelectronic devices: LEDs

In last class, we mainly looked at the interaction of light with a semiconductor material. We said that, if the energy of the light is less than the band gap it will not get absorbed and if the energy is more than the band gap then the light can get absorbed 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 or the energy increases, but the actual value depends upon the density of states of the material. We also looked at the interaction of light with say a p-type or an n-type semiconductor. Under conditions of week illumination, the increase in the concentration is highest for the minority carriers. So, if you had an n-type then the increase in concentration is maximum for the p-type or the hole. We also found that when you shine light, your N_p is not equal to n_i^2. Your system is no longer in equilibrium and when we turn 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.

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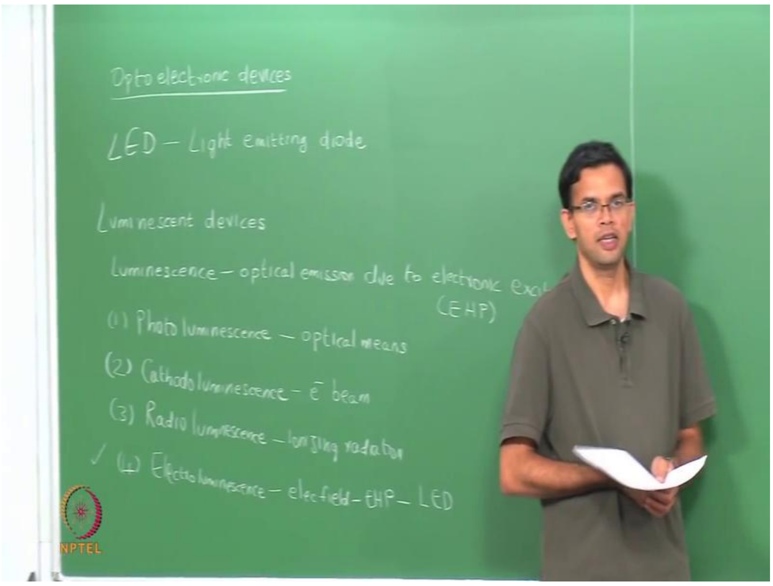

And the first device you are going to focus on is the LED or the light emitting diode. If you remember, there are mainly 2 kinds of devices, those in which you have an injection of carriers that recombine in order to give you light. So, this could be in the visible region or in the infrared or UV you also have a case where you shine light on to a material and get an output in the form of an electric current. So, LED's and lasers belong to the category of devices where by injecting carriers you produce light later we will look at a photo detector and a solar cell where the reverse process happens. So, LED's belong to the general category of luminescent devices. We can define luminescence as where we have optical radiation that is emitted because of electronic excitation. So, we will just write a working definition of luminescence this 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 to different kinds 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 ultra violet region, which creates electron hole pairs. So, this creates the electronic excitation when these electrons and holes recombine they will give light in the visible region can also have cathode luminescence in which case you have an electron beam incident on your material which creates the electron hole pairs there is radio luminescence. Here you use ionizing radiation 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 pair, so, electric field creates the electron hole pair. An LED is an example of an electro luminescence device. So, We use the external field in order to create electron hole pairs. So, if you have a p-n junction, we typically inject the minority carriers. These carriers can then recombine and see 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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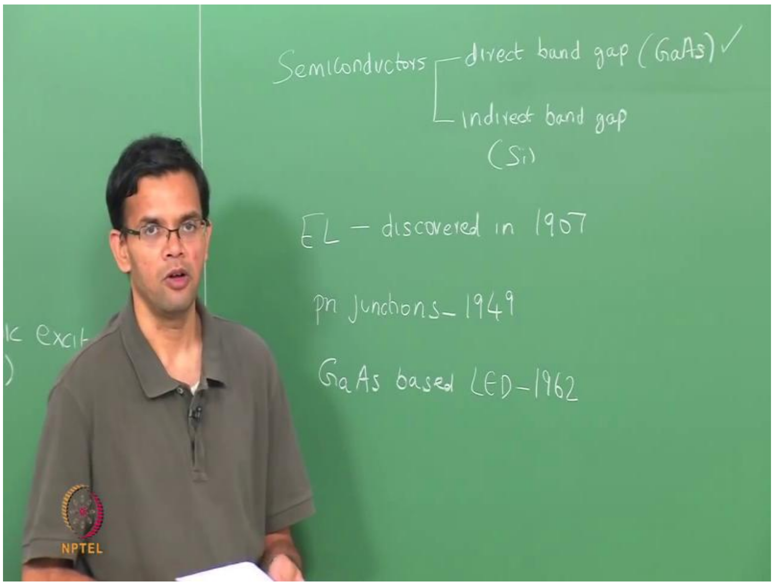

We have seen earlier that semiconductors are essentially 2 types. You have your direct band gap and you have your indirect band gap. So, you have seen that the direct band gap semiconductor is one in which the electron hole recombination proceeds with the dominant mechanism being the release of electromagnetic radiation or photons. In the case of an indirect band gap semiconductor, the energy is released in the form of heat. Silicon is an example of an indirect band gap semiconductor, gallium arsenide, the example for a direct band gap semiconductor. In the case of an LED, since we want a visible light to come out, you preferentially use direct band gap semiconductors, the phenomenon of electro luminescence. So, I will just call it E L, was first discovered in 1907, until p-n junctions were invented in 49.

There was not much work done in this area. So, p-n junctions came in 1949, but the first LED based on gallium arsenide was only in the 1960. 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 and holes can recombine and typically we want this recombination to give us light. Now, there are different kinds of transitions that are possible.

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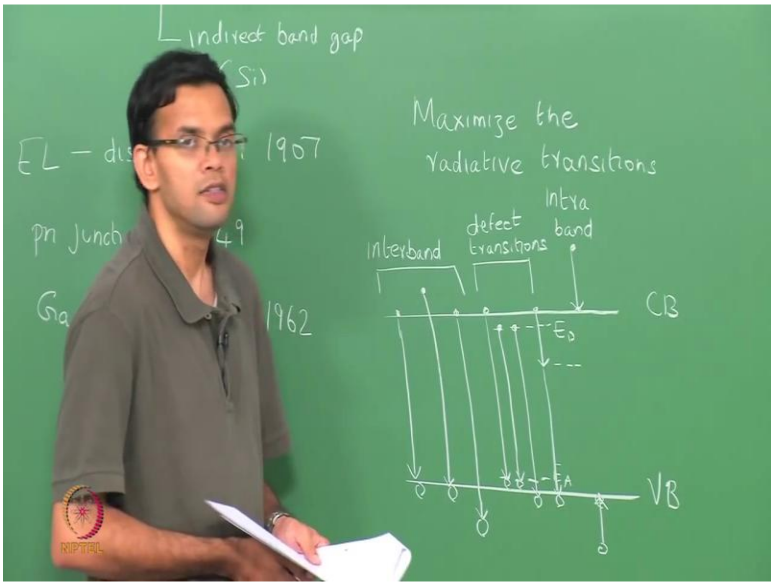

So, if I have a general picture, this is my conduction band, this is my valence band, so that different ways in which transitions can occur between the electrons and holes. So, The first kind are called inter band transitions in which can have an electron in a hole both at the edge of the conduction band and the valence band recombining can also have an electron deep in the conduction band recombining with the hole the valence band edge or you can have an electron with the conduction band edge recombining with the hole in the bulk of a valence band. So, all of these where the transition occurs from the conduction band to the valence band is called your inter band transitions.

Now, if you have a material that is doped or has some other impurities, these basically cause defects 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, it could also have acceptor levels close to the valence band. These are essentially shallow sates if you have other impurity materials or other defects they could also form states within slightly within the bulk within the band gap. So, these are shallow states, this is a deep state. So, if you have electron hole pairs that are generated then these electrons and holes can get trapped in these defect states and then recombine, those kinds of transitions are called defect transitions.

So, I can have an electron in the conduction band recombining with a hole in acceptor states. So, I will call this E_D which is my donor state, E_A is my acceptor state. I could have an electron in my donor state recombining with the hole in the acceptor state or I could have an electron in the donor state recombining with the acceptor in the valence band and sometimes you can have transitions where the electron gets trapped in a deep state 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 intra band transitions.

In this particular case, can have an electron within the bulk of the conduction band and can go to 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 the valence band. 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 defects states. In the case of LED's, we want to maximize the radiative transitions and minimize any non-radiative components. In order to increase the efficiency of the device for example, if you have defects then defects could act as traps. So, ideally when you want an LED and when we process the material we have to make sure there is no defect state that can basically cause non-radiative recombination the simplest kind of LED is essentially a p-n based junction LED. So, let me start with that first.

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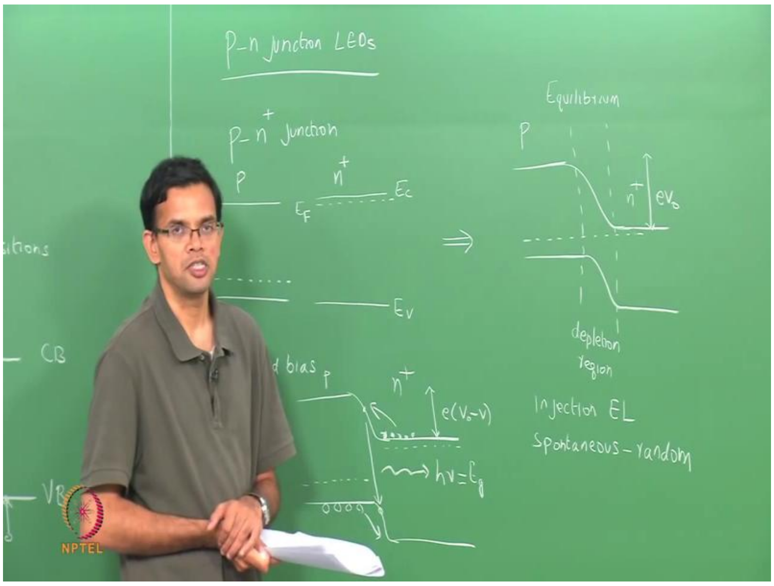

So, consider a simple p-n$^+$ junction, the n$^+$ means that the n-region is heavily doped. So, when we form a junction the depletion region is mostly within the p-side. I have my p-side E_F, E_v and E_c, this is my p-side and I have my n plus region both my p and the n are the same material. So, the overall band gap is the same. Now, I form a p-n junction when this is at equilibrium, we know that the Fermi levels line up.

So, this is the p that is the n^+. So, This is the p-n junction in equilibrium, we have a depletion region that mostly lies in the p-side and we also have a built-in or a contact potential we can forward bias the p-n junction. In this particular case, if we forward biased 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 the band diagram of this in forward bias, So, you forward the biased p-n junction, your new barrier is E_{vo} - v. So, when you forward bias we lower the barriers for the electrons and holes to go across. These are the holes.

So, these electrons and holes can recombine in the depletion region, if I have an electron here and have a hole here the electron and hole can recombine. If your material is a direct band gap material then this recombination will 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 a p-n junction and ordered to produce light. 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 are essentially a spontaneous process. So, your electrons can holes and holes can recombine not only in the depletion region they can also recombine within the bulk of the material. 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, If 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 then 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 introduced 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 p-n junction and we found that we want to maximize the electron and hole recombination within the depletion region in order to do that.

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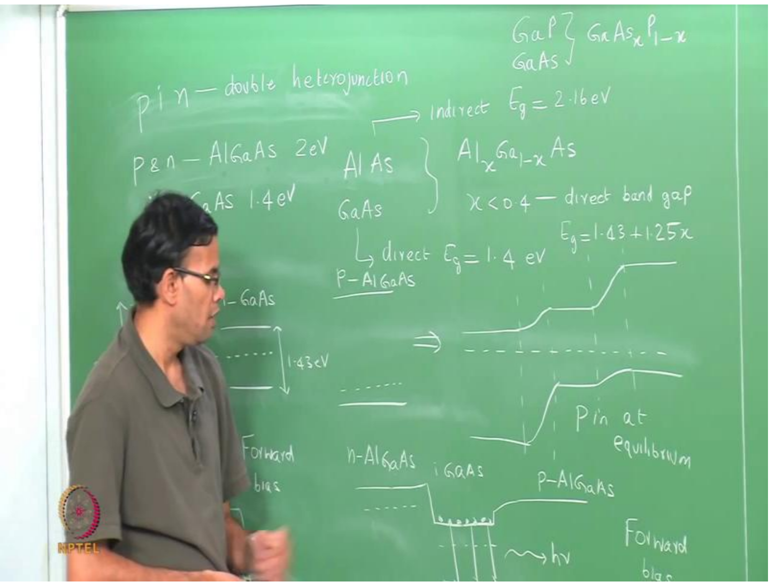

We form a pin, p is your p-type, i is an intrinsic and n is an n-type and we make the materials different, so that you have a double hetero junction. So, Let us consider an example for this, consider a p and n type material that is made of aluminum gallium arsenide and you have an intrinsic material that is made up of gallium arsenide. Now aluminum gallium arsenide is actually composed of aluminum arsenide and gallium arsenide, formula is usually given as $Al_xGa_{1-x}As$. So, when x is equal to 1, it is aluminum arsenide and when x is equal to 0, it is gallium arsenide.

Now, gallium arsenide is a direct band gap semiconductor with an e g of 1.4 electron holes, approximately it 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 1.4235 x. So, this is just an empirical relation. So, will start with aluminum gallium arsenide of band gap 2 electron volts and we have gallium arsenide band gap 1.4 electron volts. So, we are going to form a double hetero junction with these two materials.

Let me first draw the energy band gap of these materials, when they are far apart and then when they come together in order to form the junction. I have my n type, this band gap is 2 electron volts, we then have intrinsic gallium arsenide and either have an intrinsic material or a very lightly doped material, 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 is intrinsic gallium arsenide this is p AlGaAs. Now, we form a junction, So, we have 2 junctions and these are different materials. It is a hetero junction because we have two of these; this forms your double hetero junction, once again at equilibrium the Fermi levels must line up, so that this is your pin at equilibrium. Most of the depletion region will be within the gallium arsenide. So, these are your 2 junctions when you essentially have 2 depletion regions we then bias this pin.

We bias this in such a way, n is connected to negative and p is connected to positive. So, In both cases, we bias this junction in forward bias; 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 then just shift them 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 let me just mark. This is n AlGaAs. That is my intrinsic gallium arsenide that is p AlGaAs. 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 you are injecting the holes from the p side. Now because of the difference in band gaps we create this potential wells. So, we have a potential well, where electrons can accumulate in gallium arsenide. We also have a potential well in the valence band side. So, holes can accumulate these electrons and 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 has a value of around 1.4, but we are using a double hetero junction. 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 with another material for example, instead of aluminum gallium arsenide, where the aluminum actually substitutes for gallium you have another material, where you have gallium arsenide and phosphide. So that, instead of substituting in gallium, the phosphorous substitutes for arsenic, 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. This gives you gallium, again depending upon the value of x you can have a direct or an indirect band gap material. So, Once again using this, you can form a double hetero junction with gallium arsenide even there the energy of the radiation that comes out will be equal to the band gap of gallium arsenide.

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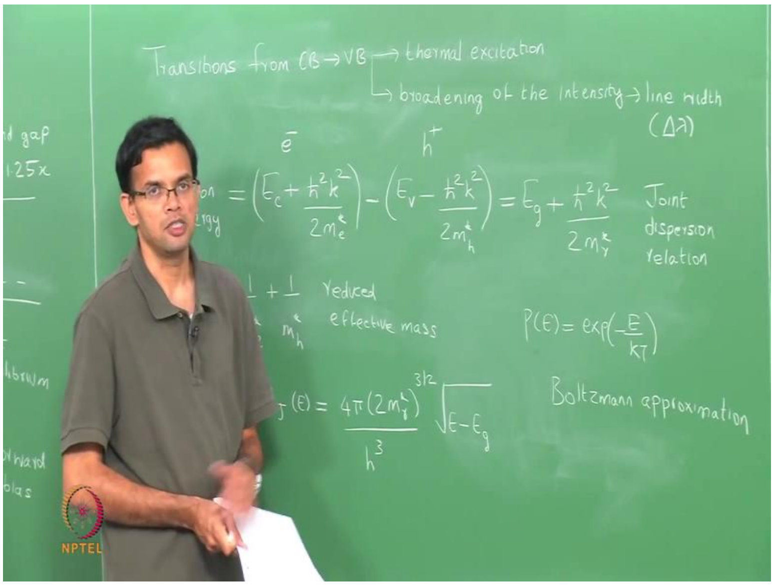

In the case of an LED, transitions occur from the valence band, from the conduction band to the valence band. Now most of the electrons and the holes are located at the edges of the conduction band and valence band, but any given temperature there will always be some thermal excitation, which means that will always have some broadening of the peak that come of the radiation that comes out where always be some thermal excitation 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 electrons in holes to occupy that is your density of states and also the probability of the occupation, that is your Fermi function. So, hυ is the energy of the photon and this is because of recombination of an electron in the conduction band with some wave vector k, with the hole in the valence band having a some other wave vector k.

In the photon energy is nothing but $E_c + \frac{\hbar^2 k^2}{2m_e^*}$. This represents the energy of the electron minus the energy of the hole $E_v - \frac{\hbar^2 k^2}{2n_h^*}$. So, this is energy of the electron this is the energy of the hole. So, These values of k can be different, but for simplicity let me just take them to be the same. In this case, this equation simplifies to $E_g + \frac{\hbar^2 k^2}{2m_r^*}$. So, this equation is called the joint dispersion relation, m_r^* is called the reduced effective mass and one over m_r^* is called reduced effective.

We can similarly define a joint density of states. So, Again, if you assume a solid with a uniform potential then the joint density of states is $4\pi 2m_r^*$. We also need the occupation probability; you can assume that the occupation is a simple Boltzmann function. So, that P(E) is just $\exp(\frac{E}{kT})$. This is a Boltzmann approximation. So, the line width which is the spread of the light that comes out from the LED because of thermal excitation it depends upon the density of states and the probability of occupation. We can show this in a graphical fashion.

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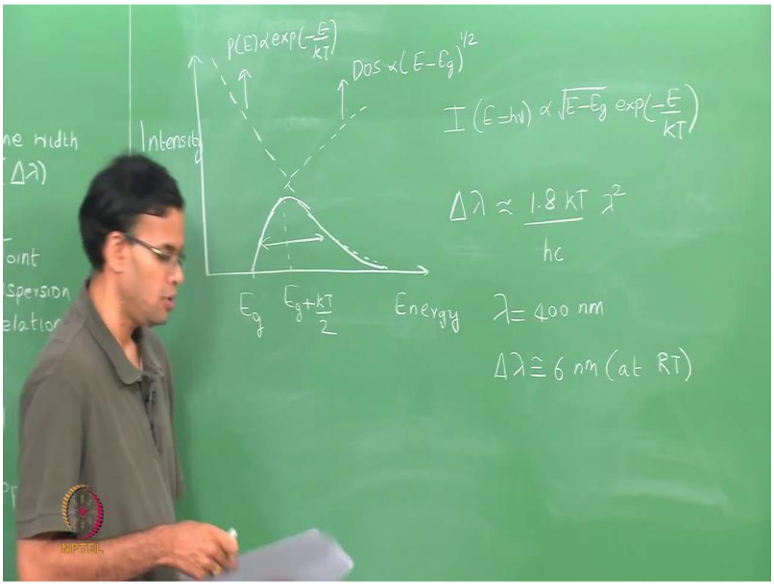

Let me plot the intensity verses the energy, y axis I have intensity, x axis I have energy. Now, we will not have any light whose energy is less than E_g because you cannot have any states in the gap. So, the minimum energy is E_g.

Now, the density of the state function increases as square root of the energy. So, this is density of states is proportional to $\sqrt{E - Eg}$. 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(E) is proportional exp(E-kT). So, the theoretical spectrum depends upon the product of these 2, so that i of some energy equal to hυ is proportional to $\sqrt{E - Eg}\exp(\frac{-E}{kT})$. If I were to plot this, this will be the spectrum of the intensity the peak usually lies $\frac{kT}{2}$ above E_g and then there is a line width. This line width $\Delta\lambda$ is approximately $\frac{1.8kT}{hc\lambda^2}$.

For example, if you have an LED which gives light at 400 nanometers. So, 400 nanometers is in the visible region and calculate a $\Delta\lambda$ which is just by substituting this here and we take temperature to be room temperature. So, $\Delta\lambda$ is approximately 6 nanometers at room temperature. So, if we have different LED materials, we can basically have light of different wavelengths. The wavelength is going to depend upon the band gap of the LED material. So, we can summarize this in the form of a plot. So, just like to look at the different LED materials.

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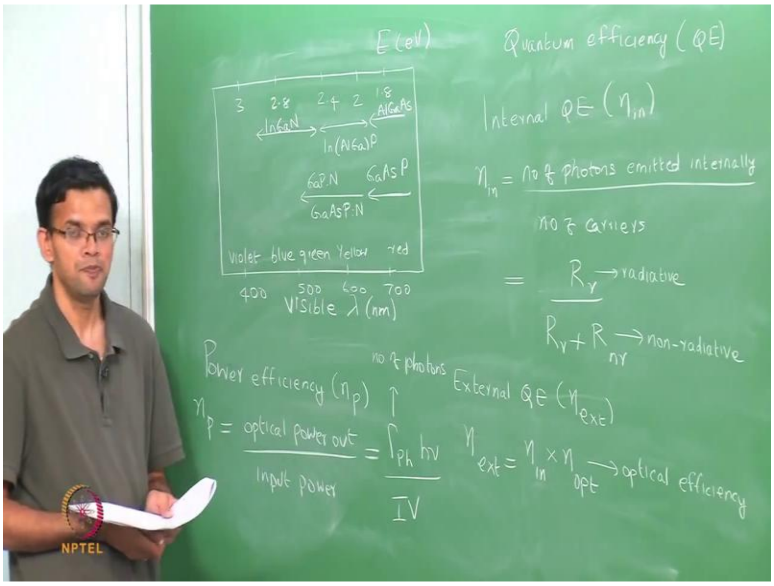

So, I will plot the visible region wavelength form of nanometers, this is 400, 500. We also plot the energy; energy is in electron volts somewhere around 3, 2.8, 2.4, 2, and 1.8. So, depending upon which region in this spectrum you want, you choose the corresponding LED material. We already saw that, if you had gallium arsenide and gallium arsenide with a band gap of 1.4, actually gives you light in the IR-region, within the blue region. If I just where 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 aluminum gallium phosphide.

So, It is an indium phosphide doped with aluminum and gallium. Already saw AlGaAs that has energy around 2 electron holes depending upon the value of x. You also have gallium phosphide based materials, this is gallium and 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 they are all based of gallium arsenide. So, gallium arsenide is a direct band gap material and we can also use it as the substrate for growing many of these LED's. In order to avoid defects, these LED's are usually grown by some vapor deposition means like chemical vapor deposition or atomic layer deposition or even or even a simple physical vapor deposition like sputtering or laser processes. So, This enables to grow the different layers with minimum defects. Again, you have to choose your materials in such a way that there is a lattice match, so that if there is any lattice mismatch that can also lead to defects. When we talk about LED's, we usually talk about a factor called quantum efficiency. I am going abbreviate this s QE.

Now, there are different matrixes for the quantum efficiency, the first one is called the internal quantum efficiency. I am going to denote this as eta i n. So, this is the number of photons that generated internally divided by total number carriers. So, η_{in}, is a number of photons emitted or generated internally divided by the number of carriers. So, this is nothing, but the ratio of the recombination rate which is radiative to the total recombination. So, R_r, which is the radiative recombination rate divided by the total. This is 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 emitter externally divided by the number of carriers. So, η 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 the transmittance of the various layers and so on. We also define something called a power efficiency η_p, which is the optical power output divided by the input power. So, η_p is the optical power out divided by the input power. The optical power output is nothing, but the number of photons, this is number of photons times the energy h mu divided by the input power which is usually just IV.

So, far we have looked at LED materials that are mainly based upon semiconductors.

You can also have LED's based upon organic materials these are called OLED's. We will not talk much about them here because you mainly deal with inorganic semiconductor materials, but LED's or OLED's also work on a similar principle. In this case, you have an organic material which is your active material sandwiched between 2 electrodes. Carriers are injected into this organic material, which then recombine to give you light. Usually OLED’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 orbital, which is similar to a valence band and a lowest unoccupied molecular orbital, which is similar to your conduction band, so that when electrons in holes recombine against this you will get light. So, There are different OLED materials are available. Again, you choose the material based upon the region of wavelength which you are interested in. So, OLED’s are useful mainly for display devices, they can easily be a thermally evaporated on to a substrate, but one of the problems with OLED’s is of course, the cost that is involved and the life span of these organic materials stability of the organic material is another issue, water damage is an issue there, but OLED’s are again another type of LED's which are based upon organic materials.

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

So, we look at lasers in the next class.