Fundamentals of electronic materials, devices and fabrication
Dr. S. Parasuraman
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Madras

Lecture – 17
Optoelectronic devices: LASERs

Let us start with the brief review of last class. So, for the last couple of classes we have been looking at Optoelectronic devices.

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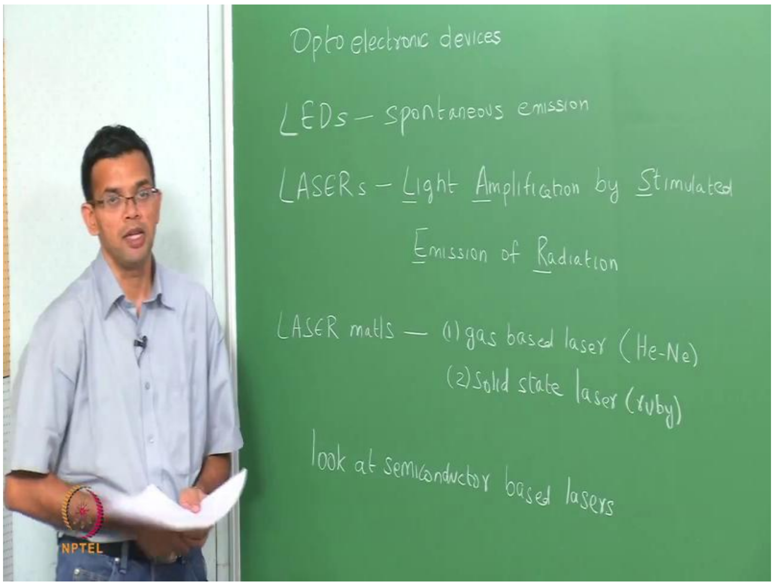

These are devices were this interaction between incident light and the electrical properties of the materiel or you have a situation where electrons and holes recombine in order to give you a light output. Last class we looked at LED's or light emitting diodes. The case of LED's we saw that we could model them as a simple p-n junction where we inject carriers, so we inject electrons from the n-side and holes from the p-sides so that these electrons and holes recombine in order to give you light. Now, depending upon the band gap of the material that determines the wave length of the light, so if you have a material like gallium arsenide then the light output is produced in the IR region, if you want light in the visible region you chose a material with the corresponding band gap. So we talked about LED's and LED's are an example of spontaneous emission, which means typically the radiation is emitted in any direction and is not necessarily in phase.

Today, we are going to look at LASERs. So, LASERs is another example of optoelectronic device where we have incident a current introduce into the material, so usually you have current that is injected which produces light. Now LASERs stand for Light Amplification by Stimulated Emission of Radiation, so the first letter in each of this comes together to give your acronym that is the laser. Now, there are large number of LASER materials that are possible for example, you can have a gas based laser typical example would be a helium neon laser. You could also have a solid state laser but based on a materiel that is not a semiconductor; for example. you have ruby lasers.

In today's lecture we are going to focus on LASERs, but you are going to spoke a specifically on semiconductor based lasers. So, what are some of the important properties of lasers that you must keep in mind?

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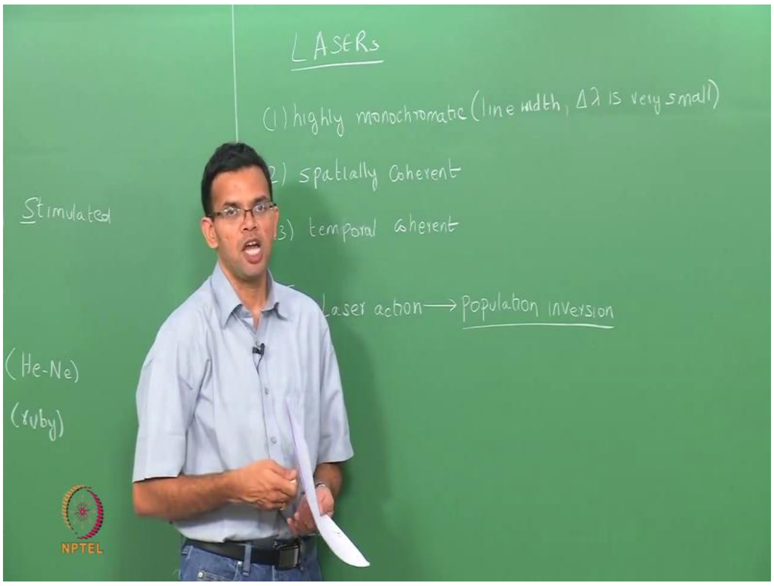

LASERs are highly monochromatic, which means the line width is really small last class we saw that the line width is nothing, but the spread the wavelength of the output radiation that is delta lambda and this line width is very small. LASER radiation is also spatially coherent and it is also temporally coherent, which means the radiation is highly in phase.

For laser primary thing we need is population inversion. So, what population inversion means? Is that we must have more number of particles in the exited states as compare to the ground state, when we achieve population inversion we have an incident radiation that strikes your materiel. This is the stimulated emission part this incident radiation causes the particles to go from the exited state to the ground state and when they do they emit an output radiations which in phase with the incident radiation. This leads the stimulated emission in basically in responsible for the laser action, so we need to create a population inversion in the system before laser action occurs. In the case of semiconductor lasers their structure is very similar to the LED's that we saw before, but there are some important points to keep in mind when we talk about semiconductor lasers.

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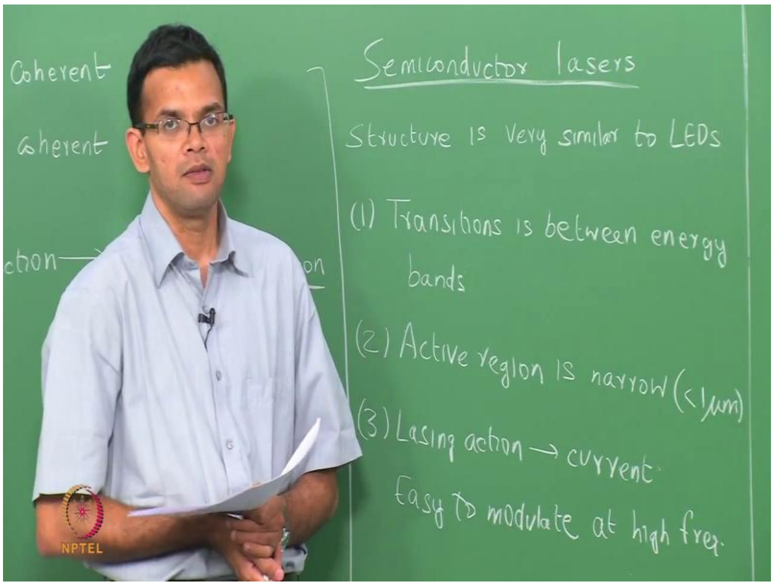

So, the structure of these LASERs is very similar to LED's, but when we compare semiconductor lasers to LASERs produced by other means for example, a gas based laser there are some important differences. The first case, here the transition is between energy bands, so one of the important criteria of lasers is that they should be highly in monochromatic, which means line width, should be extremely small. In the case of gas based laser say a helium neon laser the transition occurs between atomic states and these atomic states are very sharp which gives rise to the high monochromaticity, on the case of a semiconductor laser though the transition is usually form a conduction band to a valence band. So, These are energy band. So, there is some spread in the energy and this can affect the monochromatic nature of the light.

If we remember when we talk about LED’s, we also had a similar problem where we had an energy band because of the energy band there was a spread in the energy of both the electrons and the holes so that there was a line width and the line width increased with increase with the temperature and also with a decrease in the wavelength. So, when we talk about semiconductor lasers we have to be aware that because you are using energy bands there is a potential for a-line with issue. The active region in these lasers is usually very narrow, we will define an active region later when we look at the structure of lasers but the active region is narrow is usually of the order of nanometers so it is usually less than 1 micrometer. The advantage of this is that you can have a laser device that is very compact so think of the optical point is that you have, but the disadvantage is that it can lead to a high beam divergence.

Lasing action is usually controlled by the current. The lasing action depends upon the current because the current controls the number of carriers that are injected into the material. So, This means, it is easy to modulate these devices especially at high frequencies. We said that the structure of a laser is very similar to that of an LED. So, if you remember in the case of an LED we had electrons in the conduction band and holes in the valence band and these 2 recombine in order to give you radiation. So, if I were to show that schematically.

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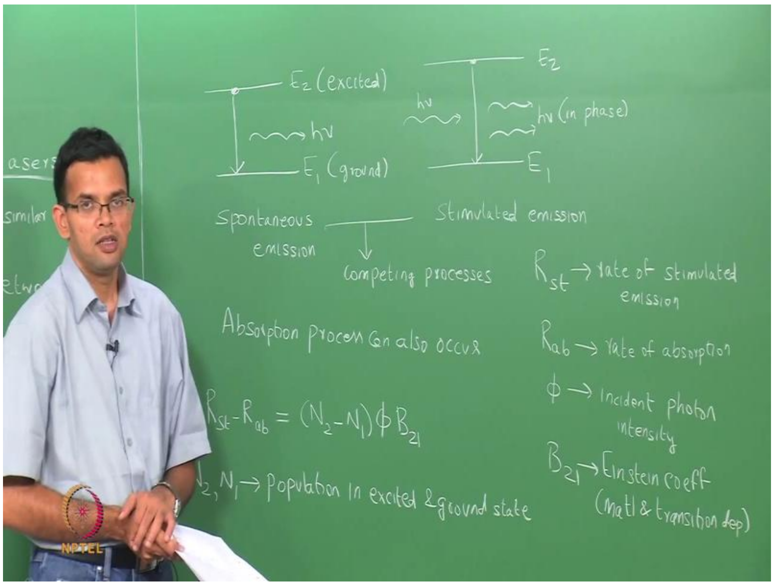

I have 2 energy bands we call one E_2 the other E_1, in a generalized sense we can also think as E_1 as the ground state and E_2 as the excited state. So, I have an electron in the excited state which basically relaxes back to the ground state, we saw that this can happen either by releasing light or releasing heat in the case of an LED or a LASER this process leads to light in the wavelength or the frequency of light depends upon the band gap. So, This is basically a spontaneous emission which occurs in an LED, you can also have stimulated emission once again I have a ground state E_1 and an excited state E_2, I have an electron in the excited state. In this particular case I have some incident radiation $h\upsilon$ and the energy of the radiation coincides with the energy of this gap when this happens the electron falls back down, this emits another photon which is in phase with the photon that is incident on your sample. The output is now essentially 2 photons that are in phase, this is an example of stimulated emission. So, In the case of a laser you can have both spontaneous emission and stimulated emission so both of these are essentially competing processes.

The reverse process can also occur, when we have an incident light instead of causing an electron to fall back from the excited to the ground this light can be absorbed by an electron the ground state and also take it to the excited state, so absorption process can also occur. So, in the case of a laser material we have a number of competing process, we have stimulated emission, we have a spontaneous emission and we have absorption. So, For ideal laser material we want to suppress the spontaneous emission and absorption at the same time promote stimulated emission. If R_{st} denotes the rate of stimulated emission and R_{ab} is your rate of absorption and φ is incident photon intensity, then we can write $R_{st} - R_{ab}$ to the rate of stimulated emission minus the rate of the absorption depends on the number of electrons that are there in the excited states minus number of electrons in the ground state times the incident photon intensity times a constant that is called the Einstein coefficient.

So, N_2 and N_1 is the population in the excited and ground state. The excited state is E_2 and the ground state is E_1, B_{21} is called the Einstein coefficient, it depends upon the material and also upon the transition. So, depends upon what the state's 2 and 1 are this is material and also upon the transition dependent. In this particular formula, we have ignored the fact that is spontaneous emission occurs we make sure that this spontaneous emission rate is much smaller than the stimulated emission. So, the only the competition is between emission and absorption. In order for R_{st} to be greater than R_{ab} we essentially want N_2 to be greater than N_1. So, is the reason why you want population inversion the case of a laser?

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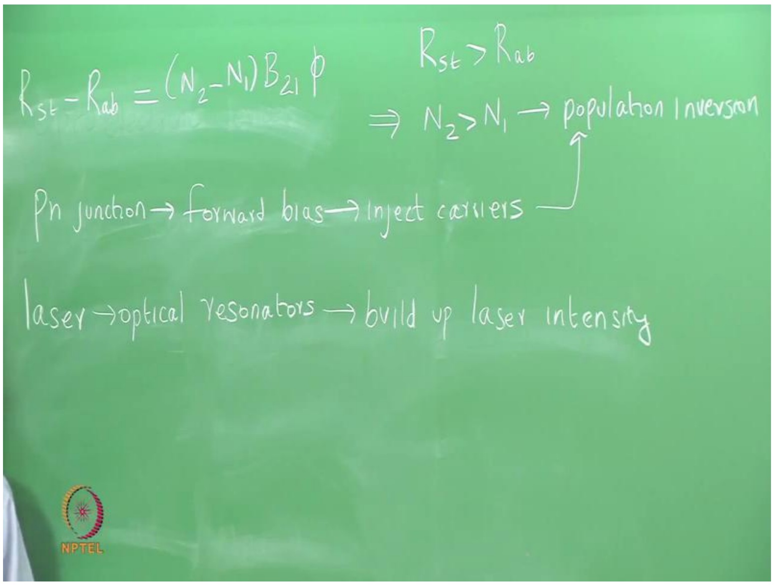

Let me just rewrite that equation, is nothing but $N_2 - N_1$ we said that if you want R_{st} to be greater than R absorbed is possible only and you have $N_2 > N_1$ 1. This population inversion is usually achieved by external means. So, the simple idea being if you had a p-n junction you could apply a forward bias, we saw earlier that when you apply a forward bias you inject carriers into your semiconductor your p-n junction so these carriers basically create the population inversion, inject carriers a willing that to here it is means that this creates population inversion. We have seen earlier there are semiconductor laser structure is similar to an LED, but we also have other optical components to the device.

So, typically a laser will have optical resonators, we will see those in a minute have optical resonators. The function of these resonators is to reflect the light, so that a certain intensity of laser is build up. So, usually 2 resonators are used one on either side, one of these is totally reflecting and the other one is partially reflecting so that the laser output comes from 1 side. Now, if you look at materials at we use for laser, these are very similar to the materials that we saw earlier for LED's. They have to be direct band gap materials usually some sort of a graded hetero-structure is used and depending upon the band gap the wavelength of the laser will be determined.

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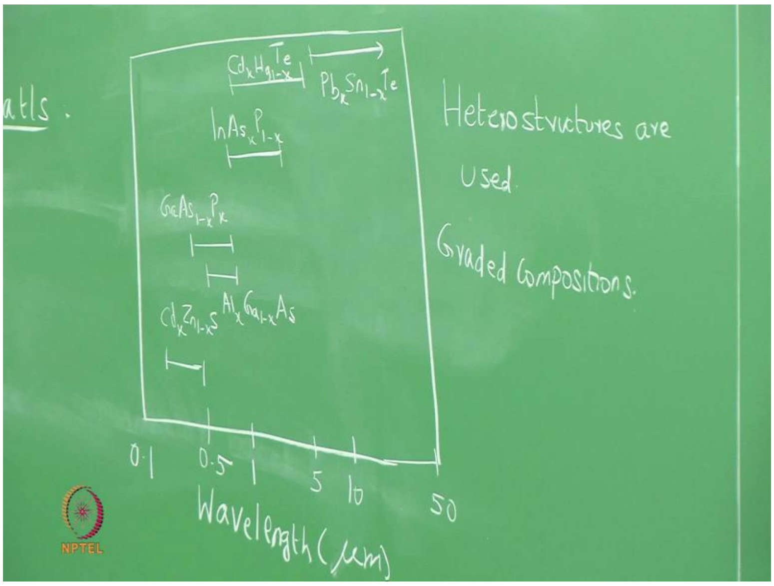

So, some examples of laser materials, I will just draw a graph to show you some of the materials used in different wavelength regions. I have wavelength on x axis, the units is micrometers 0.1 micrometers is 100 nanometers so that is the UV region, 0.5 is in the middle of the visible region 1 this is essentially a log scale. So, If you want laser light in the case of visible region you want a material whose band gap lies in the visible, these are usually two 6's so you can have cadmium, zinc sulphate. We saw that in the case of LEDs are lot of materials was based upon gallium arsenide which is a direct bind gap semiconductor most of these materials can also be used for lasers.

So, you have aluminum, gallium arsenide can also have gallium arsenic and phosphorus for the higher wavelengths or the lower bind gaps can again have indium arsenide base materials, cadmium and mercury. This is not a complete list, there are whole bunch of other materials that can be used but this sort of gives the operating wavelengths of some of the common materials. Usually Hetero-structures are used, we saw earlier in the case of LED’s, hetero-structure junctions are used in order to concentrate the carriers near the depletion region and something similar is used here and we also usually end up having graded compositions. Graded compositions are used so that you can have an epitaxial growth, if you have a huge lattice mismatch that leads to defects at the interfaces if you want to grow epitaxial layers we want to have lattice parameters as close as possible. So, graded compositions help to achieve that because they give you the wave the change in the band gap, while at the same time allowing you to grow epitaxial layers. As we mentioned earlier usually a double hetero-structure model is used for lasers.

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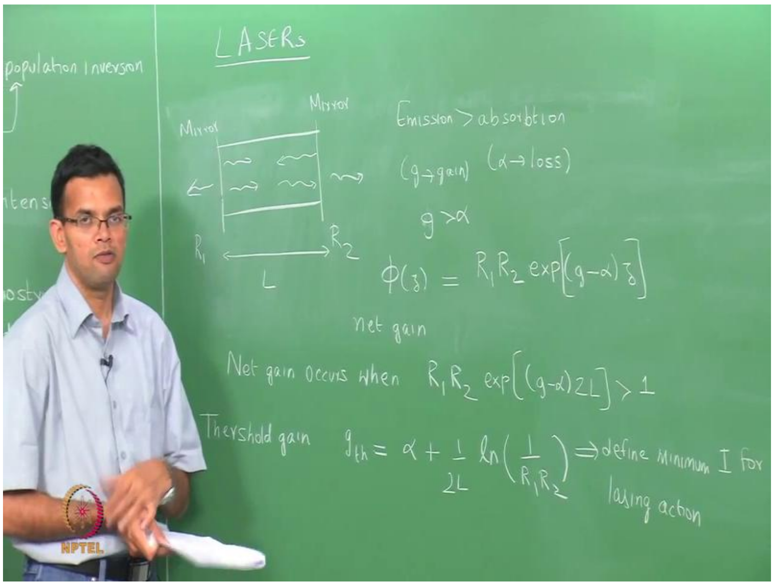

So, consider the case of a laser material of length L, there are 2 reflecting mirrors on either sides. These are your mirrors and they have reflectivity values of R_1 and R_2. You have light or laser light that is generated within the material, this light gets reflected from both the reflecting mirrors and finally some of the lights will also escape. So, in this particular material you have both emission, which is your stimulated emission and we saw that for lasing action this emission much be more than the absorption. So, If I define alpha as a loss due to absorption and g as the gain due to emission, g must be greater than alpha your gain must be more than your loss and then we define the net gain at a particular position z the net gain depends upon the reflectivity of the 2 layers times exponential g minus alpha over z.

Now, if L is the length of your laser and I have and have a light that originates at one corner, it travels a length l gets reflected from the second mirror and travels a length L back which means the total distance traveled is 2 L. So, your net gain occurs you write it here, so you have a net gain in phi is more than 1 or you have $R_1R_2\exp{(g-\alpha)}$, now the total distance traveled is 2 L because it travels from 1 mirror to the next and then get reflected and comes back. This should be greater than 1. Usually we like to define something called Threshold gain, which tells you how much current you need to supply in order for lasing action to occur. Once again you must supply enough current so that the emission is more than the absorption. So, we define a Threshold gain, $I_{th} = \alpha + \frac{1}{2L}\ln(\frac{1}{R_1 R_2})$. This intern helps you to define the minimum current that is required for lasing action.

So, in this particular example the 2 reflectors help to confine the laser in the plain of the device. But, we also need to confine the light within the active layer, so that light does not escape from the top or the bottom. So, This is done by usually choosing a graded structure with different refractive indices, so that you have total internal refraction and the light kept within the active region. So, let me include that as well and draw a schematic of the laser structure. So, We want to confine the beam in the lateral direction done by using reflectors and we also want to confine the beam in the vertical direction this is called Wave guiding.

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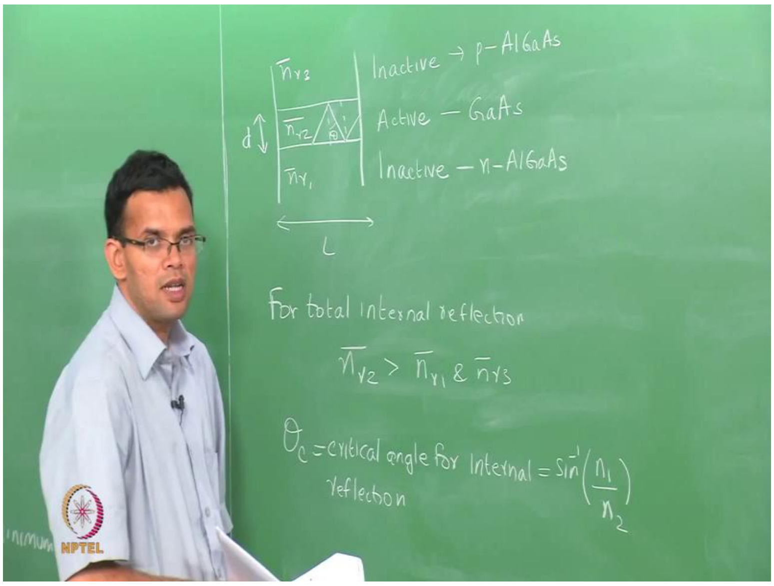

This is usually done by choosing materials with different refractive index. So, these are my 2 mirrors, I have an active region the length is L there is an active region of width d. The active region is the region where your electrons and holes recombine in order to produce the laser light. There also 2 inactive regions, so these can be used in order to confine the electrons and holes within the active region, but we also want materials in such a way in order to provide for wave guiding. For example, you can have an active region that is made a gallium arsenide and your inactive regions could be P type aluminum gallium arsenide on one side and n type aluminum gallium arsenide on the other.

So, let n_2 or n_{r2} be the refractive index of gallium arsenide and n_{r3} and n_{r1} be the refractive index of the inactive aluminum gallium arsenide layers. For total internal reflection, we want n_{r2} to be greater n_{r1}, n_{r3}. So, when this happens light can just get reflected within the active layer and will not escape itself. So, We can define this angle theta and the critical angle theta for total internal reflection is given by theta c is a critical angle for total internal reflection, so which is nothing but $\sin^{-1}(\frac{n_1}{n_2})$. So, consider the case of a gallium arsenide, aluminum gallium arsenide material.

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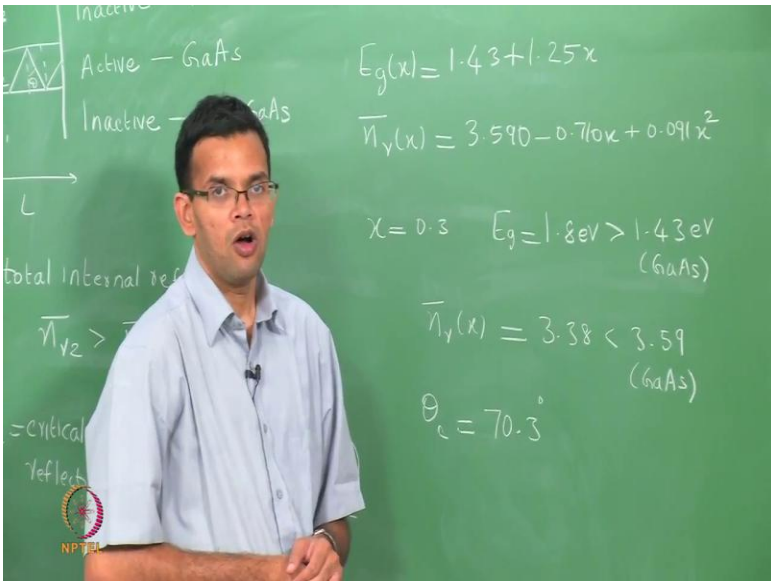

So, aluminum gallium arsenide can be written $Al_xGa_{1-x}As$. So, This is a structure that is formed by combining aluminum arsenide and gallium arsenide and the property depends upon the value of x. For example, the band gap E_g as a function of x is nothing but 1.43 plus similarly the refractive index also depends upon the value of x. So, This gives a refractive index that is lower than that of a gallium arsenide so that you can have total internal reflection. For a particular value of x say 0.3, your band gap E_g calculated is 1.8 which is greater than the band gap of gallium arsenide which is 1.43.

Similarly, you can calculate the refractive index for x is equal to 0.3 which is 3.38 which is less than 3.59 which is the value of gallium arsenide. So, We can calculate the critical angle for total internal reflection; theta c comes out to be 70.3 degrees. So, of your incident radiation as angle greater θ_c then will have total internal reflection, if it is less than theta c it will be partially reflective. By using both optical reflectors at the edges and also by wave guiding so by using a graded structure with different refractive indexes you can basically have lasing actions. So, this action is similar to that of an LED where in the case of an LED we do not have these optical resonators or these wave guiding structures.

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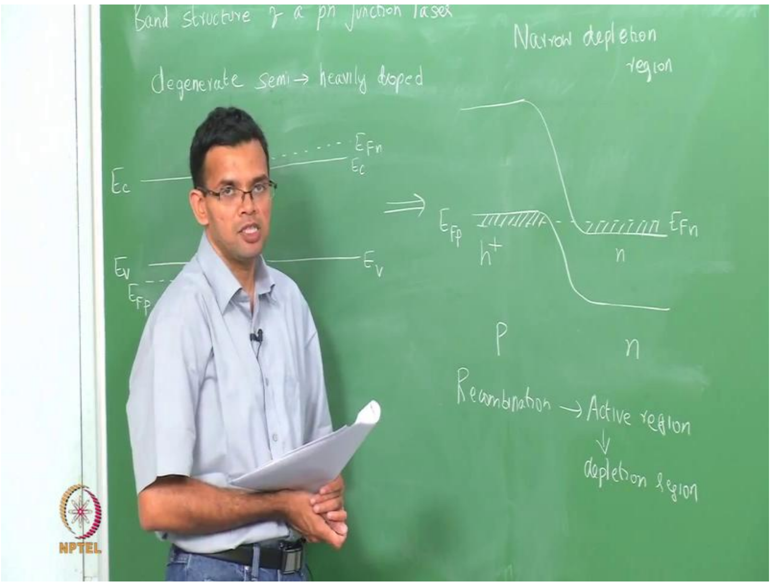

So, consider the band structure of a simple p-n junction laser. We want to achieve population inversion so we want excess carriers or excess electrons in the conduction band, excess holes in the balance band. So, we start with heavily doped p and n type materials and we usually used degenerates semiconductors. So, These are heavily doped we saw degenerate semiconductors earlier, where we said at the doping level was so high that the impurity levels form a band which can combine with valence or the conduction band. In this particular case the Fermi level will lie within the band. So, we can have a p side is E_c E_v and the Fermi level lies within the valence band similarly, can have a conduction side we can have the n side where the Fermi level lies within the conduction band. So in this particular case, if you form a p-n junction with these 2, so these are the excess holes that are there in the p side, these are the excess electrons on the n side.

The depletion region is also very narrow because we have heavy doping, so when we apply a forward bias the electrons are injected from the n side to the depletion region the holes are injected from the p side these electrons and holes combine within the active region which is the depletion region and that give you a laser, have recombination in the active region in the active region is nothing but the depletion region. We can modify this structure in this particular case it is simple p-n junction based upon the same material, just like in the case of LED's we can use hetero-junctions or we can also go for double hetero-structure so let us look at an example of that.

So, We already saw earlier that we had a gallium arsenide aluminum gallium arsenide based system. So, the advantage of that in the case of wave guiding was that total internal reflection is also possible, but aluminum gallium arsenide also has a higher band gap in gallium arsenide, so this helps to confine the carriers within the active region which is the gallium arsenide region.

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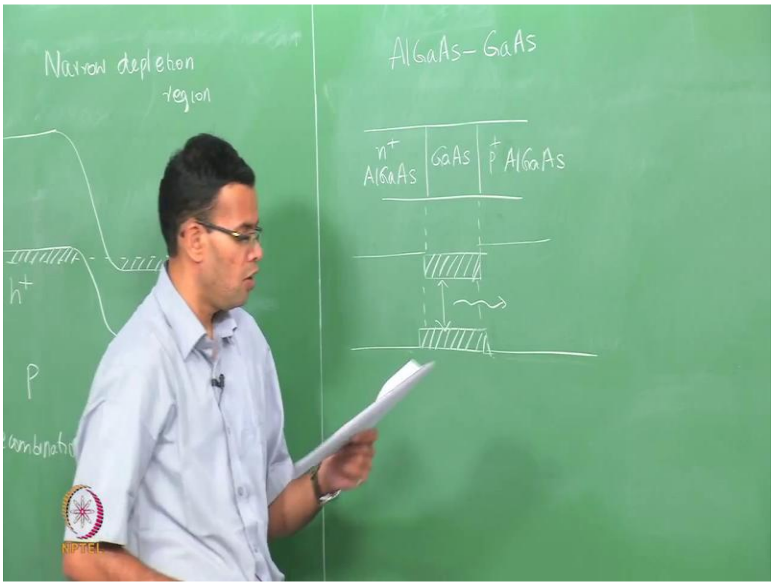

If you have an aluminum gallium arsenide gallium arsenide based structure n type and then p type aluminum gallium arsenide. So, when we forward bias this double hetero-structure junction once again we can inject electrons from the n side onto gallium arsenide and inject holes when the p side onto gallium arsenide, then these then recombine to give your laser light. So, we were to draw a very basic band picture, I just draw the extra lines. So, that this central region is your active region have electron and holes and these can recombine to give you light. This kind of a structure can then be incorporated with mirrors in order to produce the lasing action. The intensity of the output light depends upon the number of electron whole pairs or the current.

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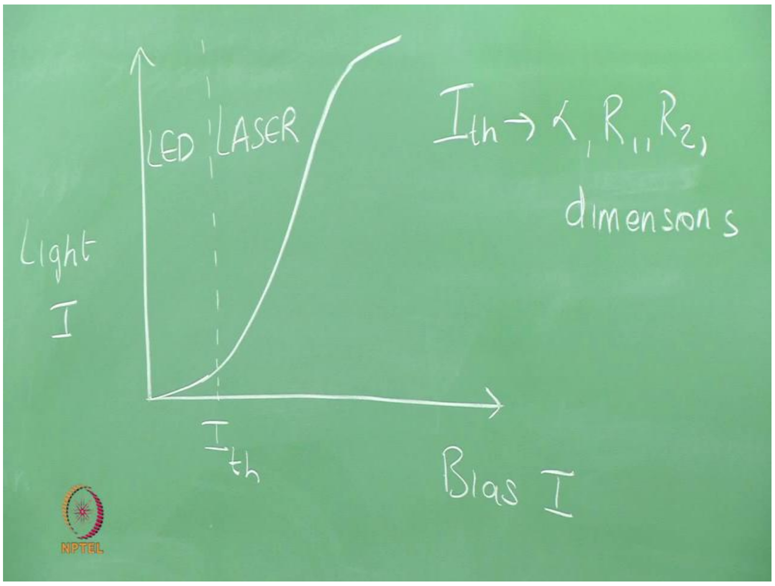

So, if I were to plot the light intensity versus the bias current. The bias current defines how many electron hole pairs are injected. There is a threshold value below which the material behaves as an LED an above which behaves as a laser. Define an I threshold below which it is an LED and above which it is a laser. We saw earlier that this threshold current depends upon the threshold gain, which says that you must have emission greater than absorption. This threshold value not only depends upon the material with also depends upon the design, so it depends upon alpha the reflectivity of your mirrors and the also the dimensions of the sample. So, this is just a simple double hetero-structure base laser. Can also have specialty laser for example, you can have quantum confinement within this active regions in order to give you quantum well based lasers.

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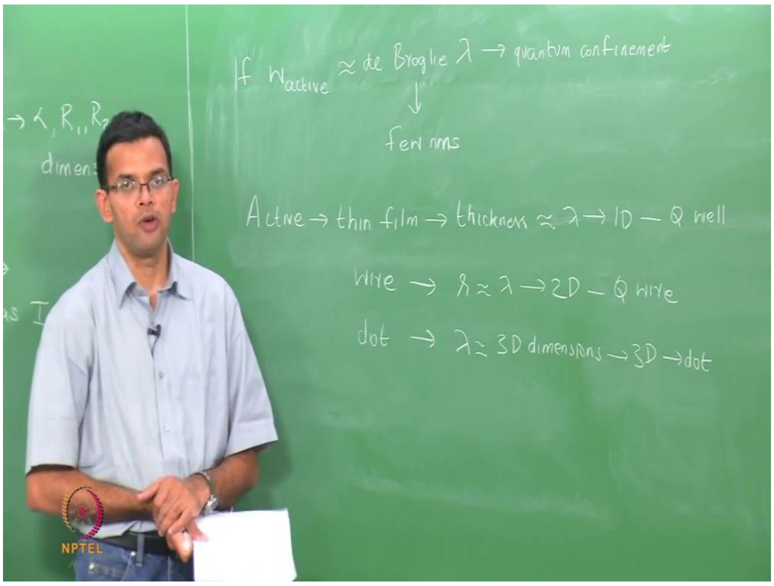

In the case of a double hetero-structure laser like the one we just saw with gallium arsenide and aluminum gallium arsenide, the active region is the gallium arsenide region. If the width of the active region is comparable to de Broglie wavelength, in that particular case we can get quantum confinement within the active region. Now the de Broglie wavelength is usually of the order of few nanometers. So, one can do a simple calculation relating the thermal energy to the momentum in form which we can calculate the wavelength, if you do that is usually of the order of a few nanometers. So, of the active regions is only a few nanometers thick whether it is in 1D, 2D or 3D you can get different orders of quantum confinement. If the active region is in the form of a thin film then only the thickness is of the order of the de Broglie wavelength, so the thickness is comparable to lambda.

In this case, you have 1D quantum confinement this is called Quantum well. On the other hand if it is in the form of a wire where your radius of the wire is of the order of lambda, that is the case of 2D quantum confinement that is your quantum wire and if it is in the form of a dot, then all 3 dimensions, so you can just say for all 3 dimensions or of the order of lambda. So, Now, you have 3D quantum confinement, so you have a dot. Whenever you have quantum confinement, you have discrete energy levels so that when you make quantum lasers because you have discrete energy levels it also leads to a much narrow over line width. So, we have looked at 2 Optoelectronic devices where we have an input electric current giving you an output light both LED's and LASERs.

The next class, we are going to look at the Reverse problem, where we shine light on to a material and look at the output electrical current.

We will look at photo detectors in next class and after that we look at solar cells.