Lecture - 17
Optoelectronic devices: LASERs

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

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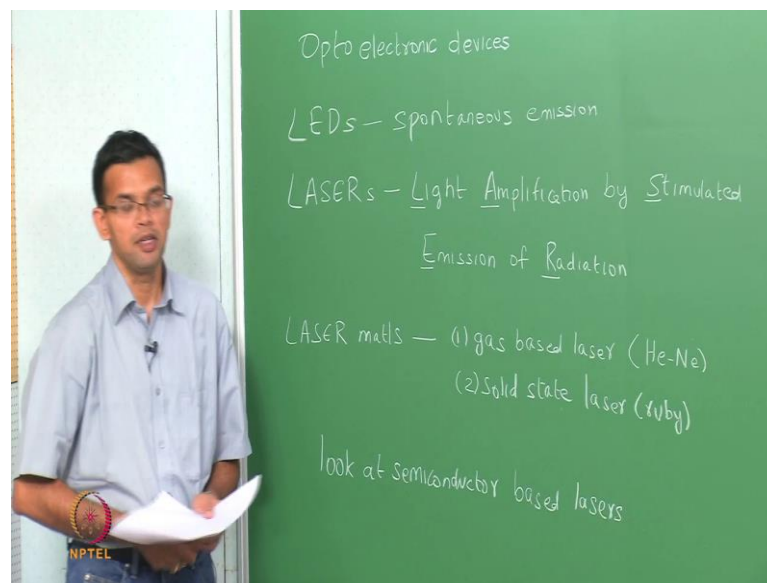
So, these are devices where this interaction between in incident light and the electrical properties of the material or you have a situation, where electron and holes recombine in order to give you a light output. Last class we looked at LEDs or light emitting diodes, in the case of LEDs we saw that could model them as a simple p-n junction where we inject carriers. So, we inject electrons from the n sides and the holes from p the sides.

So that, these electrons and holes recombines 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 their region. If you want light in the visible region, you choose a material with the corresponding band gap.

So, we talked about LEDs and LEDs are example of an 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 current introducing to the material. So, usually you have current that is injected which produces light.

Now, LASER stand for Light Amplification by Stimulated Emission of Radiation. So, the first letter in each of this comes to together to give you the acronym that is the LASER. Now there are large number of lasers material that are possible for example, you can have a gas base laser typical example would be a Helium-neon laser you could also have a solid state laser, but based on material that is not a semiconductor.

For example, you have Ruby lasers, in today's lecture you are going to focus on lasers, but you are going to spoke us specifically on semiconductors based lasers. So, what are some of the important properties of laser that you must keep in mind.

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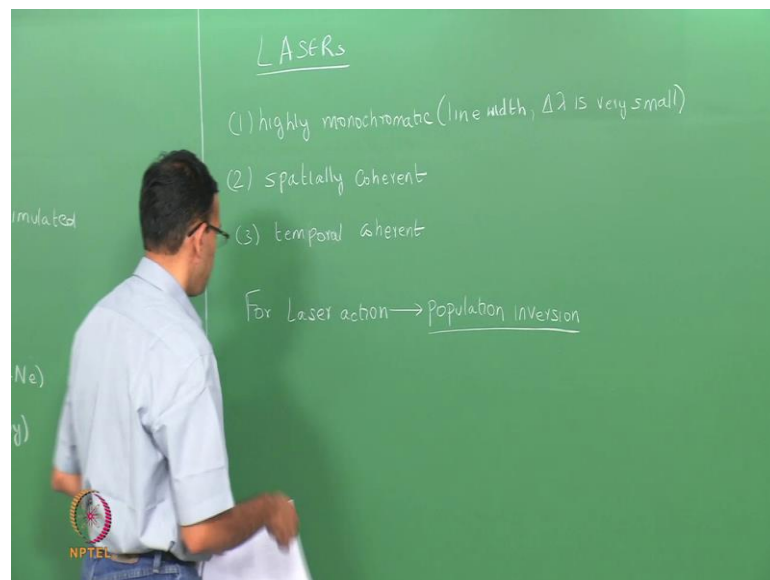
LASERs are highly monochromatic which means, the line width is really small. Last class we saw, the line width is nothing, but the spread in the wave length of the output radiation that delta lambda and this line width is very small. Laser radiation is also

spatially coherent and it is also temporarily coherent which means, the radiation is highly in phase. For laser the primary thing we need is population inversion.

So what population inversion means is that, we must have more number of particles in the excited state as compare to the ground state. When we achieve population inversion, we have an incident radiation that strikes your material this is the stimulated emission part. This incident radiation causes the particles to go from the excited state to the ground state and when they do, they emit and output radiation which is in phase with the incident radiation.

So, this leads to stimulated emission and basically it's responsible for the laser action. So, we need to create a population inversion in this system before laser action occurs. In the case of semiconductor lasers, the structure is very similar to the L E Ds that we saw before, but there are some important points to keep in mind when we talk about semiconductor lasers.

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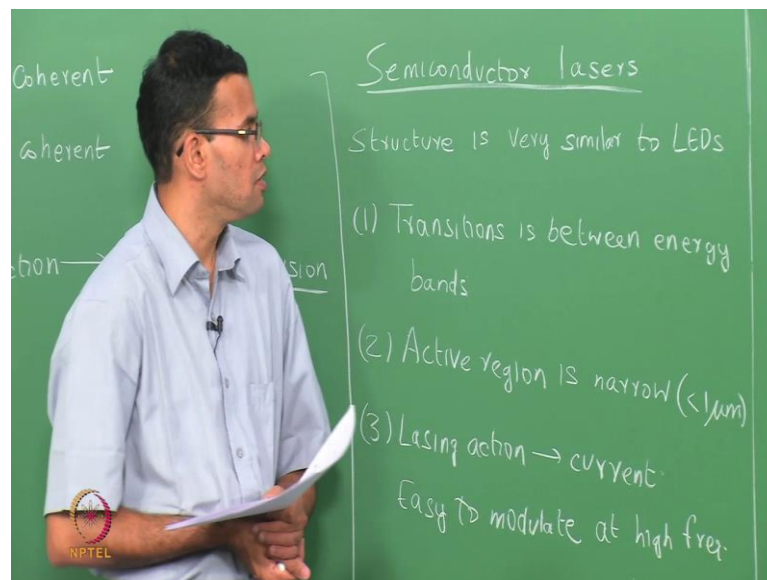
So, the structure of these lasers is very similar to LEDs, but when we compare semiconductor lasers to lasers produced by other means. For example, like gas based lasers there are some important differences. The first case here the transition between the

energy bands. So, 1 of the important criteria of lasers if that they should be highly monochromatic which means, the line width should be extremely small.

In the case of the gas based laser say, a Helium-neon laser the transition occurs between atomic states. These atomic states are very sharp, which gives rise to the high monochromaticity on the case of semiconductor laser though the transition is usually from a conduction band to a valance band so, these are a energy bands. So, there is some spread of the energy and this can affect the monochromic nature of the light.

If you remember when we talk about LEDs we also had a similar problem, where we had an energy band because of the energy band there was a spread in energy of both the electrons and the holes. So, that there was line width and the line width increased with increase in temperature also, with decrease in the wave length. So, when we talk about semiconductor lasers we have to be aware that because, you are using a energy bands there is potential for a line width issue.

The active region in this lasers is usually very narrow, we will define the active region later when we look at the structure of this lasers, where the active region is narrow is usually of the order of nanometer. So, it is usually 1 micrometer the advantage of this is that you can have a laser device that is very compact. So, think of the optical point that you have, but the disadvantage is that it can lead to high beam divergence. Lasing action is usually control by the current the lasing action depends upon the current.

Because, the current controls the number of carriers that are injected in to the material so, this means it is easy to modulate these devices especially at high frequencies. So, 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 have electrons in the conduction band and holes in valance band in these 2 recombined in order to give you radiation.
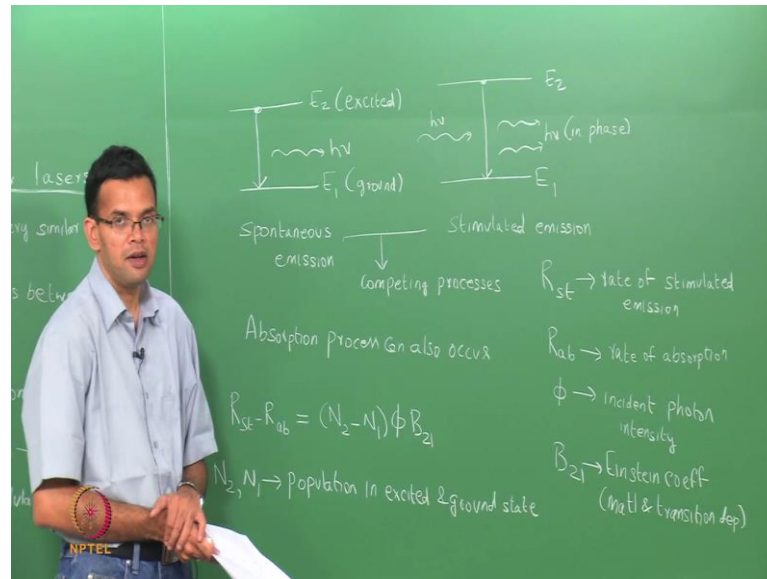
So, if I wait to show that schematically I have 2 energy bands: we call 1 E2, the other E1 in a generalize sense we can also think as a E1 as a ground state and E2 at the excited state. So, I have an electron in the excited state which basically relaxes back to the ground state. We saw that, this can ha happen either by releasing light or by releasing heat in the case of an LED or a LASER this process lead to light and the wave length of frequency of light depends upon the band gap.

So, this is basically a spontaneous emission which hackers in LED. You can also have stimulated emission, once again I have a ground state E1 and an excited state E2 I have an electron in the excited state. In this particular case I have some incident radiation h mu and the energy of the radiation coincide with the energy of this gap, when this happen the electrons fall back down. So, this emits another photon which is in phase with the photon, which is incident on your sample.

Now your output is essentially 2 photon that are in phase this is an example of stimulated emission. So, in the case laser 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 absorb by an electron in the

ground state and also take to the excited state.

So, absorption process can also occur so, in the case of a laser material we have a number of competing processes. We have stimulated emission, we have a spontaneous emission and we have absorption. So, for and ideal laser material we want to suppress the spontaneous emission and absorption at the same time promotes stimulates emission. If Rst denote: the rate of stimulated emission and Rab is: rate of absorption and phi is the incident photon intensity.

Then, we can write Rst minus so, the rate of stimulated emission minus the rate of absorption depends on the number of electrons. There are there in the excited states minus number of electrons in the ground states, times the incident photon intensity times the constant that is called the Einstein co-efficient. So, N2 and N1 is the population in the excited and ground state.

The excited state is E2 and the ground state is E1, B21 is called the Einstein coefficient it is depend upon the material and also upon the transition. So, it depends upon the what this states 2 and 1 are this is material and transition depend. In this particular formula, we have ignore the fact that is spontaneous emission occurs we make sure that this spontaneous emission rate is much smaller then this stimulated emission. So, the only competition is between emission and absorption.

In order for Rst to be greater than Rab we essentially want N2 to be greater than N1. So, it's the reason why you want population inversion in the case of a laser. So, let me just re write that equation.

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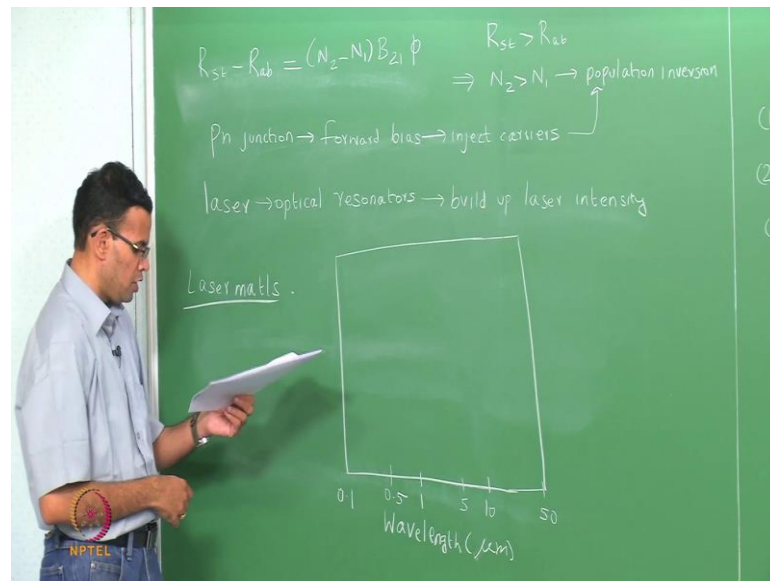
Rst minus Rab is nothing, but N2 minus N1 and we said that if you want Rst to be greater than Rab is possible only; when we have N2 greater than N1. So, this population inversion is usually achieved by external means. So, the simple idea being if you had p-n junction you could apply a forward bias we saw earlier that when you apply a forward bias you inject carriers into your p-n junction.

So, these carrier basically create the population inversion inject carriers availing that to here which means, this creates your population inversion. So, we have seen earlier that the semiconductor laser structure is similar to 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 the function of this resonators is to reflect the light.

So that, a certain intensity of a laser is build up; the usually I used to build up laser intensity. So, usually 2 resonators are used: 1 on either side 1 of these totally reflecting and the other 1 is partially reflecting so that, the laser output comes from 1 side. And now, if you look at the material we use for lasers this are very similar to the materials that we saw earlier for LEDs.

So, they have to be direct band gap materials usually some sort of a grader Hydro

structure is used and depending upon the band gap the wave length of the laser will be determined. So, some examples of laser material I will just draw a graph to show you some of the material is used in different wave length regions. So, I have wave length on x axis the unit is micro meter 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 we want a material whose band gap lies in the visible.

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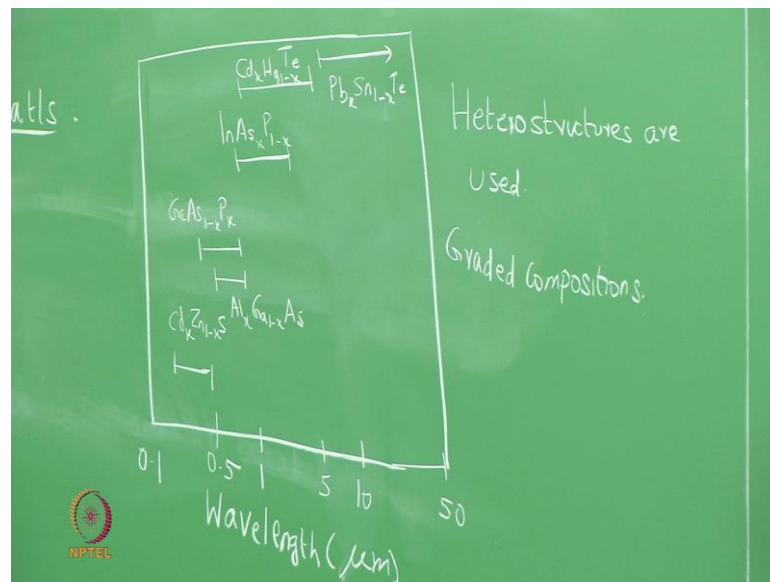
These are usually the 2 sixes so, you can have Cadmium, Zinc sulfide. We saw in the case of LEDs a load of materials based upon Gallium Arsenide, which is direct band gap semiconductor most of these materials can also be used for lasers. So, you have Aluminum, Gallium Arsenide can also have Gallium, Arsenic and Phosphorous for the higher wave lengths or the lower band gaps can gain have Indium Arsenide based materials Cadmium and Mercury.

So, this is not a complete list there are whole bunch of other materials that can be used, but this sort of gives the operating wave lengths of some of the common materials. Usually Heterostructures are used we saw earlier in the case of the LEDs

Heterostructures junctions are used in order to concentrate the carriers near the depletion region and something similar is used here. And we also, usually induct 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 composition help to achieve that because, they give you the wave the change in the band gap well at the same time allowing you to grow epitaxial layers. As we mention earlier usually a double Heterostructures model is used for lasers.

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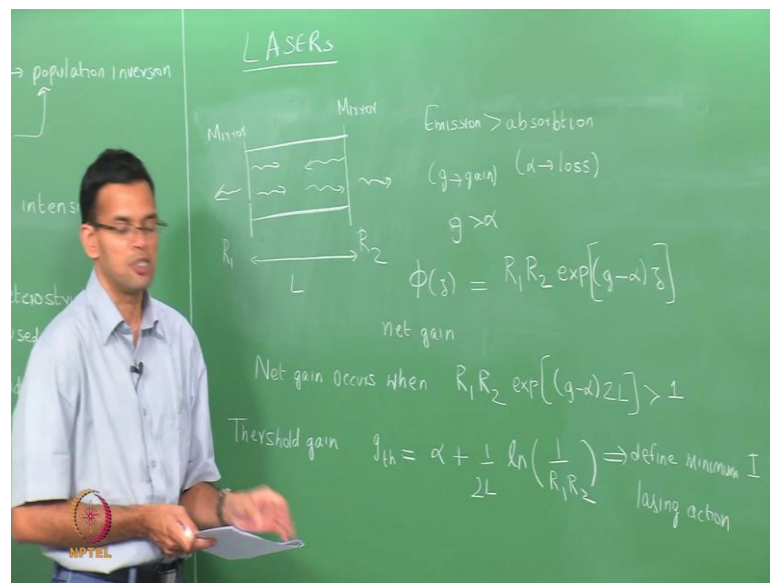
So, consider the case of a laser material of length l there are 2 reflecting mirror in either sides. So, these are your mirrors and they have reflectivity values of R1 and R2. So, you have light or laser light that is generated within the material these light this light get reflected from both the reflecting mirrors and finally, some of the light will also escape. So, in this particular material you have both emission which is your stimulated emission and we saw that lasing action this emission must 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 a loss. And then we define the net gain at a particular position g the net gain depends upon the reflectivity of 2 layers times exponential g minus alpha over z. Now, if L is the length of your laser and a higher and I have a light that originates at 1 corner it travel a length L get reflected from the second mirror. And travels a length l back which means the total distance travel is to l.

So, your net gain occurs let me write it here. So, you have a net gain and 5 is more than 1 or we have R1 times R2 exponential g minus alpha now the total distance traveled is 2L. Because, it travel 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 call threshold gain, which tells you how much current you need to supply in order to 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 it is equal to alpha plus 1 over 2L non of 1 over R1 and R2. So, this interns helps you to define the minimum current t hat 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 does not escape in 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 reflection and the light is kept within the active region. So, let me included 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.
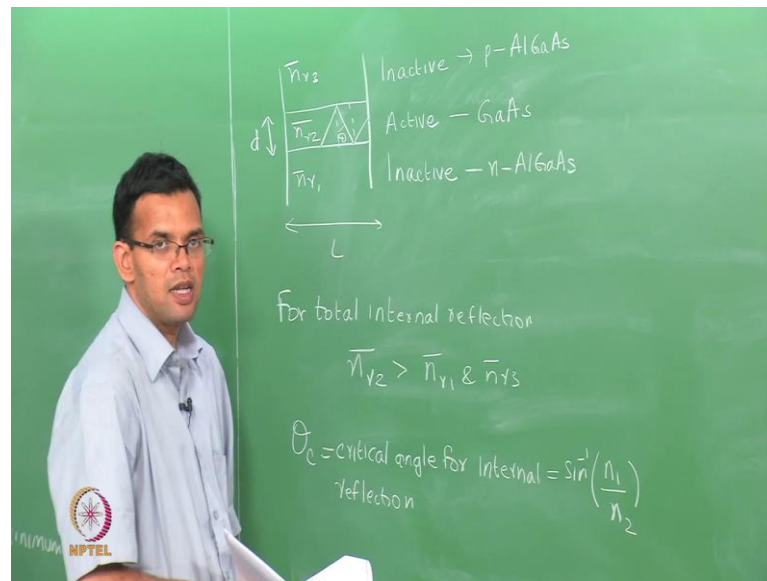
So, this is usually done by choosing materials with different refractive index. So, this are my 2 mirror I have an active region the length is L there is an active region of width d. The active region is the region, where you electrons and holes recombined in order top produce the laser light. There also 2 inactive regions so, these can be used in order to confine the electrons and holes within the active regions, but we also wants materials in such a way in order to provide for wave guiding.

For example, you can have an active region that is made of Gallium Arsenide in your active regions could be p-type Aluminum gallium arsenide on 1 side and n-type Gallium Arsenide on the other. So, let n2 or nr2 be the refractive index of Gallium Arsenide and nr3 and nr1 be the refractive index of the inactive Aluminum Gallium Arsenide layers, for total internal reflection we want nr2 to be greater nr1 nr3.

So, when this happens light can just get reflected within the active layer and will not escape outside. So, we can define this angle theta and the critical angle theta for total internal reflection is given by theta c your critical angle for total internal reflection. So, it is nothing, but sin inverse n1 over n2. So, consider the case of your Gallium Arsenide Aluminum Gallium Arsenide material.
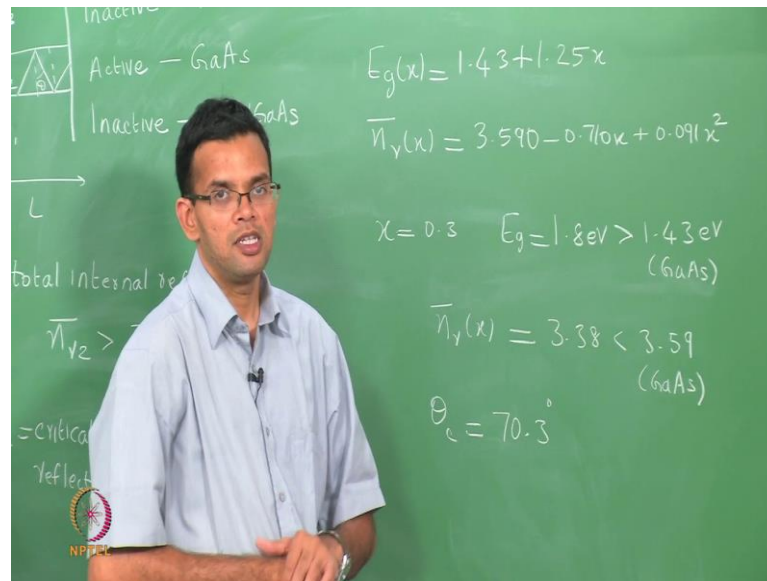
So Aluminum Gallium Arsenide cab be written as Aluminum x Gallium 1 minus x As. So, this is a structure that is formed by combining Aluminum Arsenide in Gallium Arsenide and the property depends upon the value of x. For example, the band gap Eg has a function of x is nothing, but 1.43 plus similarly, the refractive index also depends upon the value of x.

So, this give a refractive index that is lower from that of Gallium Arsenide so that, you can have total internal reflection. For a particular value of x say 0.3 your band gaps Eg calculate 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 for 3.38 which is less than 3.59 which is the value for Gallium Arsenide.

So, we can calculate the critical angle for total internal reflection. So, theta c comes to be 70.3 degrees. So, if your incident radiation has angle greater then theta c then we will have total internal reflection, if it is less then theta c it will be partially reflect. So, by using both optical reflectors at the edges and also by wave guiding so, by using a grader structure with different refractive indexes you can basically have lasing action. So, this action is similar to that of an LED, but in the case of an LED we do not have this optical resonators or this wave guiding structures.

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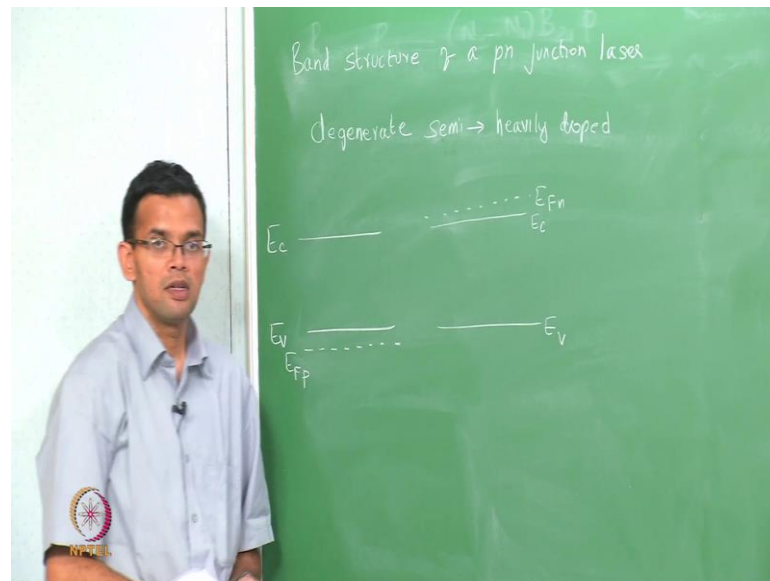
So, consider the band structure of a simple p-n junction Laser. We want to achieve population inversion. So, we want excess carriers or excess electrons in the conduction band and excess holes in the valance band. So, we start with the heavily doped p and n type materials and usually use degenerate semiconductors.

So, these are heavily doped we saw degenerate semiconductors earlier where we said that the doping level was so high that the impurity levels form a band which can combine with the valance or the conduction band. In this particular case the Fermi level will lie within the band. So, we can have a p side this is Ec Ev and your Fermi level lies within the valance band.

Similarly, you can have a conduction sides or you can have the n sides where the Fermi level lies within the conduction band. So, in this particular case if you form a p-n junction with this 2.

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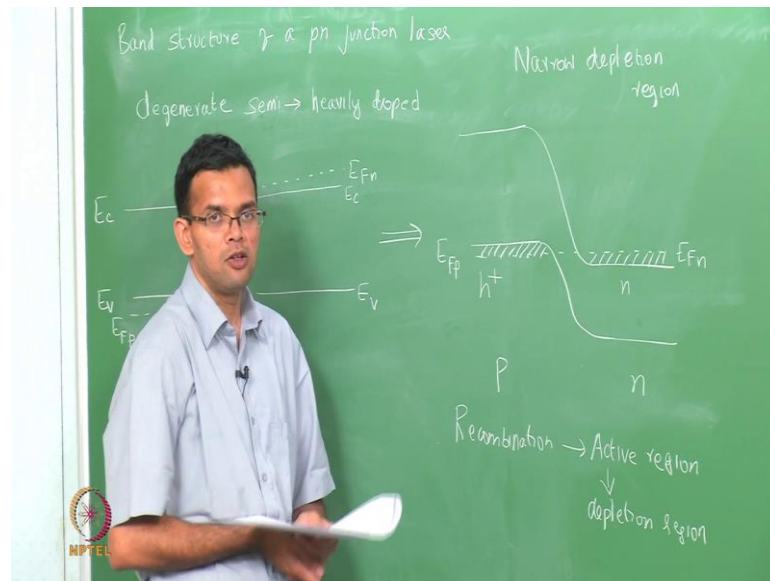
So, these are the excess holes that there on the p side, these are the excess electrons on the n side. The depletion region is also very narrow because, we have heavy doping. So, when we apply a forward bias the electron are injected from the n side to the depletion region the holes are injected from the p side these electrons and holes combine within the active region, which is the depletion region and that gives you your laser.

So, we have recombination in the active region and the active region is nothing, but the depletion region. We can modify the structure in this particular case it is a simple p-n junction based upon the same material just like in the case of LEDs, we can use Hetero junctions or we can also go for a double Heterostructure. So, let us look at in 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 was 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 regions.

So, if you have a Gallium Arsenide region gallium arsenide based structure n-type and then p-type Aluminum Gallium Arsenide. So, when we forward bias this double Heterostructure junction once again we can inject electrons from the N side on to Gallium Arsenide and inject holes on the p side on to Gallium Arsenide then these then recombine to give your laser light.

So, if were to draw a very basic band picture draw there extra lines so that, this central region is your active region have electrons and holes and these can recombine to give you light. So, 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 depends upon the number of electron whole pads or the current.

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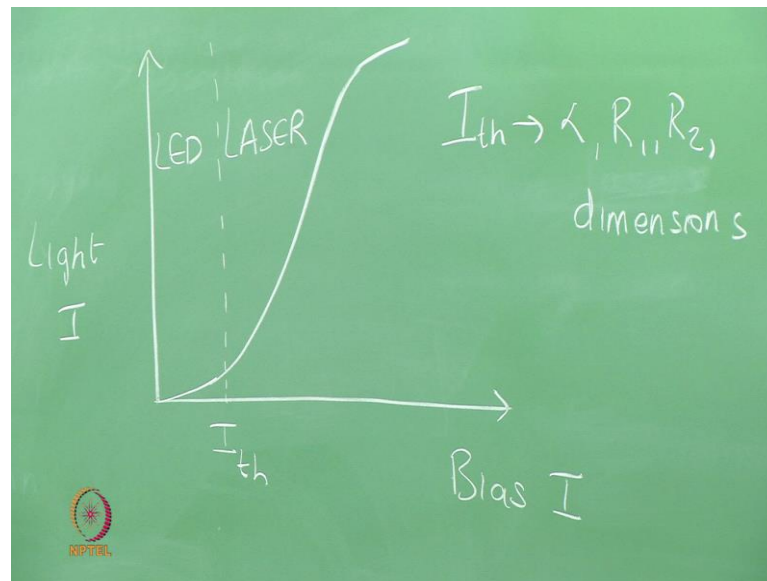
So, if I were to plot the light intensity posses the bias current. So, the bias current defines how many electron whole pads are injected there is a threshold value below which the material behaves as and LED and above which behaves as a laser. Define and I threshold below which its and LED and above which it's a laser. We saw earlier that this threshold current depends upon the threshold gain which says that, you must have emission greater than absorption.

So, this threshold value not only depends upon the material, but also depends upon the design. So, it depends upon alpha the reflectivity of your mirrors and also the dimension of the samples. So, this is just a simple double Heterostructure based laser can also have specialty lasers. For example, you can have quantum confinement within this active region in order to give you quantum well based lasers.

In the case of the double Heterostructure laser like the 1 we just saw with Gallium Arsenide and Aluminum Gallium Arsenide the active region is the Gallium Arsenide region.
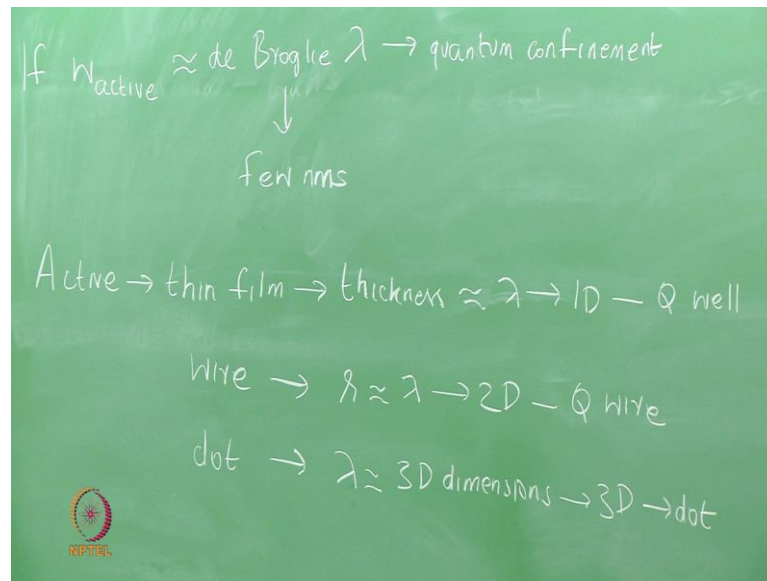
If the width of the active region is comparable to the de Broglie wave length, in that particular case you can get quantum confinement within the active region. Now the de Broglie wave length is usually of the order of few nanometers. So, 1 can do a simple calculation relating the thermal energy to the momentum and from which we can calculate the wave length if you do that is usually of the order of few nanometers.

So, if the active region is only a few nanometers tic, whether it is in 1D, 2D or 3D you can get different orders quantum confinements it your active is in form of a thin film. So, it is a thin film then only the thickness is of the order of the de Broglie wave length. 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 wire were your radius of the wire is of the order of the lambda that is case of 2D quantum confinement that is a 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 3D quantum confinement so, you have a dot whenever, you have quantum confinement you have discreet energy levels.

So that, when you make quantum lasers because you have discreet energy levels it also

leads to a much narrower line width. So, we have looked at 2 optoelectronic devices where we have an input electric current giving you an output light both LEDs and LASERs. The next class we are going to look at the reverses problem, where we shine light on to a material and look at the output electric current. You will look at photo detectors in next class and after that we will look at solar cells.