Semiconductor Optoelectronics
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Lecture - 33
Semiconductor Laser-I Device Structure

We will start with the semiconductor lasers, the device, structure, characteristics and various designs with the special characteristics. Semiconductor lasers are first invented in 1962 by 4 different groups almost simultaneously.

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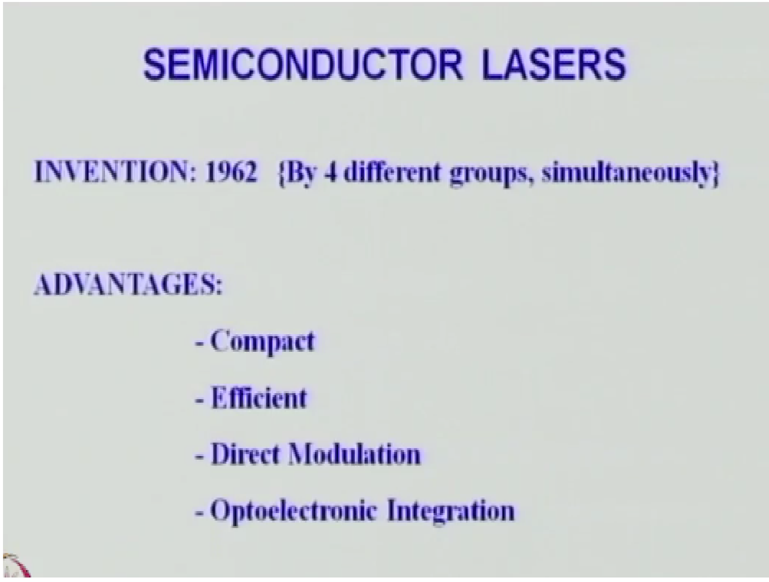

So, usually one does not assign credit to any one group but the main advantage is of semiconductor lasers are they are compact, we already know the size that is involved is very small. A helium neon laser with about 1-foot-long gives you about 5 milliwatt of power, a small semiconductor laser can give you 100 milliwatts of power. It is very compact and very efficient. Efficiency is measured in terms of power conversion efficiency.

It is very efficient. Normal bulk lasers have efficiencies between 0.1 to 1% normally except the carbon dioxide laser which has high efficiency. Otherwise most of the bulk lasers are very inefficient in terms of power conversion, electrical to optical. Whereas semiconductor lasers are very efficient. Efficiency is normally are 20 to 30% electrical to optical conversion and there are devices people have shown efficiency in excess of 60% that is just consuming 2 milliwatt of electrical power.

2 milliwatt which is very low and giving 1 milliwatt of optical power that is really very efficient. The other important characteristic why semiconductor laser is used in communication and all the consumer application is the possibility of direct modulation. Most of the bulk lasers modulation here we referred to any signal or any communication is send through modulation.

So most of the bulk lasers we use, the lasers you use, the laser output and put an external modulator here.

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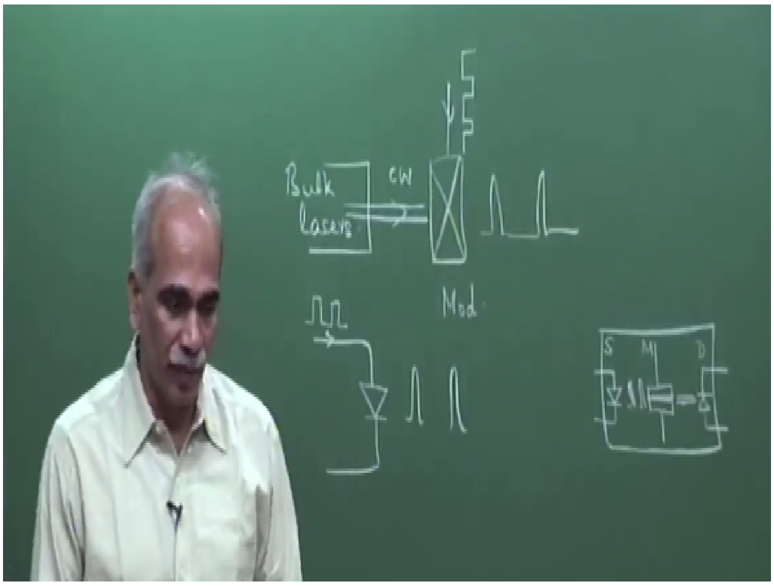

So this is an external modulator. Whereas in semiconductor laser **our** most practical purposes accept when the speed involves is more than several gigabit per second. It is sufficient you can directly modulate; you simply bias the modulation current here. Bias the direct current by the modulating signal and you will get accordingly the output. So this is called direct modulation that is the modulating signal is directly super imposed on the diode bias currently.

Whereas in bulk lasers you usually have a CW output here continuous wave output and the modulator then biases, modulator then modulates with the required. So you feed the modulating signal here on to this. The modulator takes input, the digital input or the modulated bit pattern is set to the external modulator and whereas in the case of semiconductor lasers direct modulation and this is very helpful.

It saves use of one additional component, one additional device is not required you can directly modulate by modulating the current. Optoelectronic integration this is quite clear, optoelectronic integration here. We are referring to integration of source, detectors and modulators. There are chips now available where you have several components which are integrated on a single chip.

So you may have source at this end. I am just systematically showing, a source here which is giving digital output, optical output which is couple to a modulator. For example, electro absorption modulator which is also semiconductor based. So you couple it to a modulator and you can also detect the output. The detectors are also semiconductor based.

So the source modulator here and the detector and of course the channel itself where you can further have other effects the channel, the optical channel is also everything integrated on a single chip. So this is what we are referring to as optoelectronic integration on a single chip. But usually the number of components on a chip are not very large, a few components only 4, 6, 8 not more than that normally on a chip.

Whereas when you talk of VLSI or microelectronics you are talking of millions of components on a chip. So we do not have that kind of numbers but nevertheless you can integrate some of the active devices and components on a single chip this is what we referred to as optoelectronic integration.

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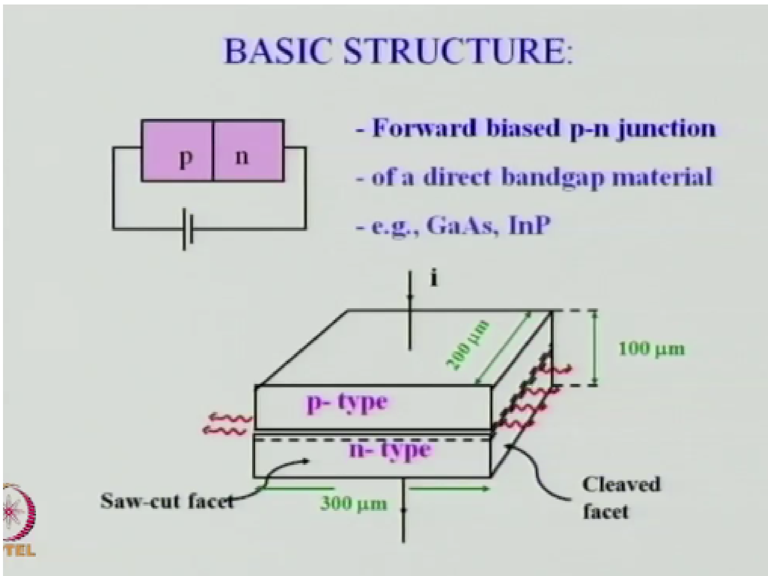

The basic structure of a semiconductor laser is as I have discussed in detail. It is a forward biased PN junction here. It is a forward biased PN junction and made of a direct band gap material such as Gallium arsenide, Indium phosphide, we have discussed in enough detail.

But I would like you to see the structure here what is shown with the typical dimensions. So the structure this is the length dimension, length and this is the width dimension.

So, typically 300 micron here width is about 200 micron and thickness of the substrate is approximately of the order of 100 micron. It has 2 cleaved facets. Yesterday I mentioned about cleaved facets acting as mirrors at the 2 ends it has cleaved facets, so that light which is generated and light which is travelling in this direction here forms a resonator. Whereas **it also** the other 2 ends which are here and on the other side.

That is this facet and on the back side here are saw-cut, usually saw-cut that is cut with a saw or so that you have a rough surface in this side. On the other 2 sides there is rough surface otherwise light could as well have built up in this direction like this. It could have gone back and forth in this direction which means light could have come from here that is from this output here.

So you will not light to come in from a particular direction and therefore 2 sides are saw-cut the other 2 sides are cleaved. So that resonator is form in that direction and current flows through the device.

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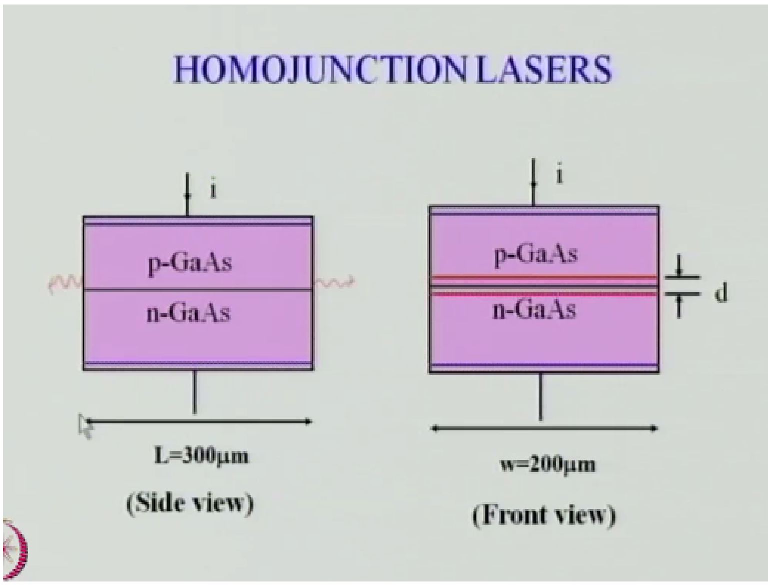

Originally when it was discovered in 1962 they were homojunction lasers that is simple PN junctions highly doped P and N materials forming a PN junction and the depletion region or the active region here as a thickness of approximate d, which is typically 1 to 2 micron in a

PN junction and this is the front view. The width is about 200 micron, the side length is about 300 micron as we saw in the previous slide.

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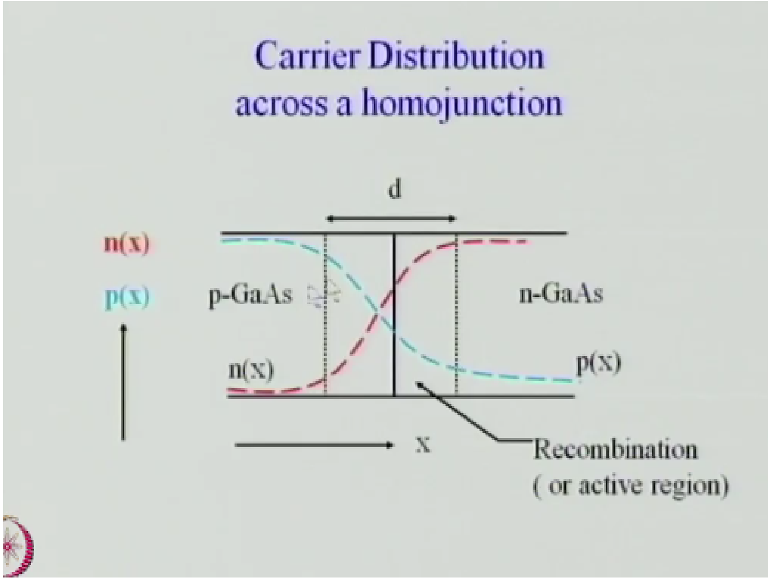

The carrier distribution across the junction these are basics which we have already discussed in detail. So let me quickly go through them. The carrier distribution across the junction we shown here, so this is n (x) here the carrier density across the PN junction this X direction, so P side and N side. Here P is the majority carrier and it drops down across junction and this is our recombination region or the active region. Very quickly recalling.

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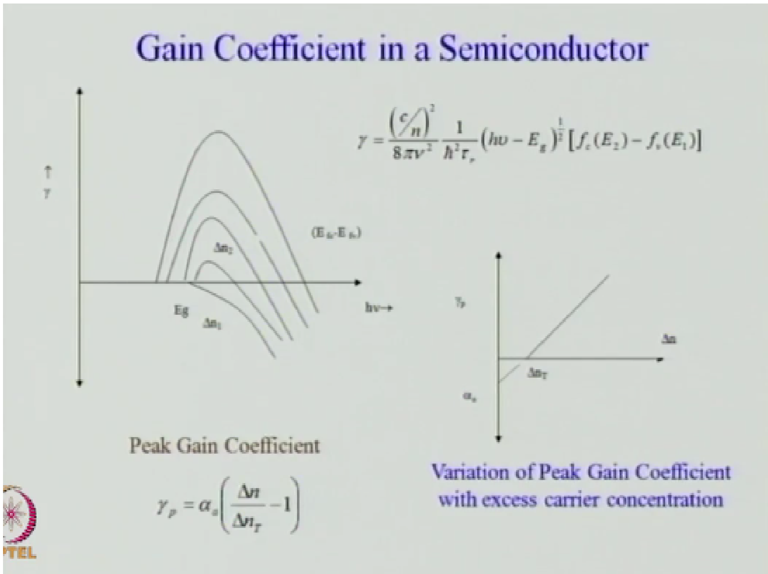

Now let us see this, gain coefficient in a semiconductor. We have got this expression for gain coefficient, I hope those of who at the back are able to read it. A little small but I wanted to show the 2 figures on the same diagram some discussion, some explanation is required here.

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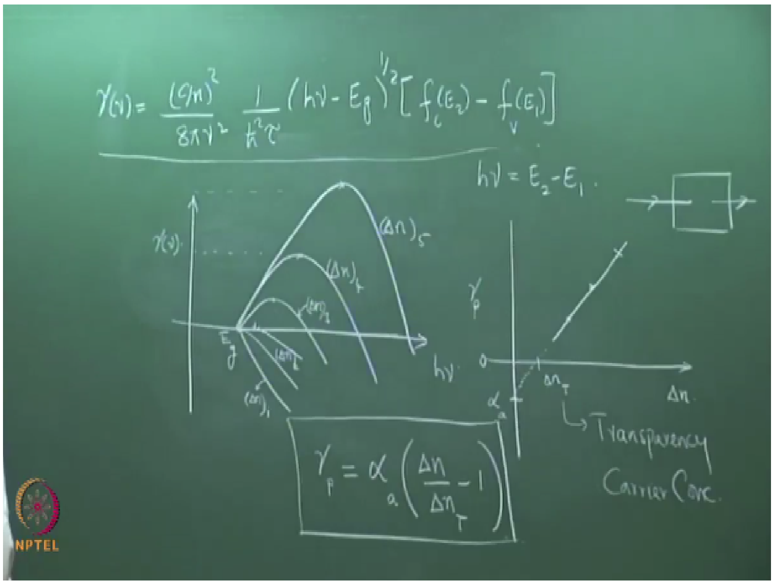

We have got this expression for gain coefficient gamma = c by n whole square 8 pi nu square into 1 over H cross square tau r. H cross square tau into h nu - Eg. Actually H cross square tau we had used tau there. So let me not write tau r. H cross square tau H nu - Eg to the power half into that is fg last one is fg that is fc of E2 the equilibrium and fv of E1.

E2 is a level such that this is for gamma of nu, gain coefficient gamma of nu and E2 and E1 are such that h nu = E2 – E1. So, all the quantities in this expression we know and this if you plot for different energies this is what we have already plotted. So here, when you are in the last class also we have discussed this. This is h nu and this is gamma, gamma of nu and this point is Eg, is that alright? h nu, gamma of nu versus h nu.

So, this is for different values, of these are for different values of delta L. So, this is the plot for the active medium. The peak gain coefficient here gamma p, gamma p, gamma p here, so these are the peak gain coefficient corresponding to various values of delta n. So, if you call this as delta n0 or delta n1, delta n2, delta n3. This is delta n 1 2, okay. It is not delta n1. So, various values of delta n delta n3 delta n4 and delta n5.

There are different values of gain coefficient here. The peak gain coefficient if you plot this gain coefficient the second curve what it shows is this is not theoretical, this is in practice it is found that gamma p if you plot for different values of delta n then they all form almost in a straight line. The peak value and this quantity here is alpha a when delta n is 0 which means you are not pumping the semi-conductor is in, there in no excess carrier concentration.

Which means you are not pumping it. This is the absorption coefficient alpha a and the value of delta n where neither gain nor, so this is 0 here. S, the value of delta n at which the peak gain, please see there is peak here but so if I take this particular delta n here you can see that the peak is just 0. For this value of delta n when the transition takes place from negative side to positive side there is a place where the peak is at 0.

And that value of delta n is called the transparency carrier concentration delta nT, capital T standing for transparency. So, transparency carrier concentration and the equation of the line is therefore written as you can see this, so this is gamma p this what I have plotted is the peak value of gamma for different values of delta n. So, gamma p = alpha a into delta n by delta n T – 1. You can see this in delta n = delta nT gamma p is 0 and when delta n = 0 it is – alpha a.

So, here alpha a this is the equation of the straight line. It is approximately a straight line. It is not any theoretical this one. So, it happens that it is approximately a straight line. But this can be used reasonably with a good approximation gamma p = alpha a into delta n – delta nT. Please recall that delta nT is the carrier concentration when the peak gain coefficient is 0.

Gain coefficient is 0 means it is neither absorbing nor amplifying or the medium acts like as if it is transparent there is no absorption, no amplification means what this transparent. So, no change in the intensity, so you have a medium here and if this is transparent whatever is input goes out. So, neither amplification nor absorption that is why the name transparency carrier concentration delta nT, okay alright. So, this slide is the main.

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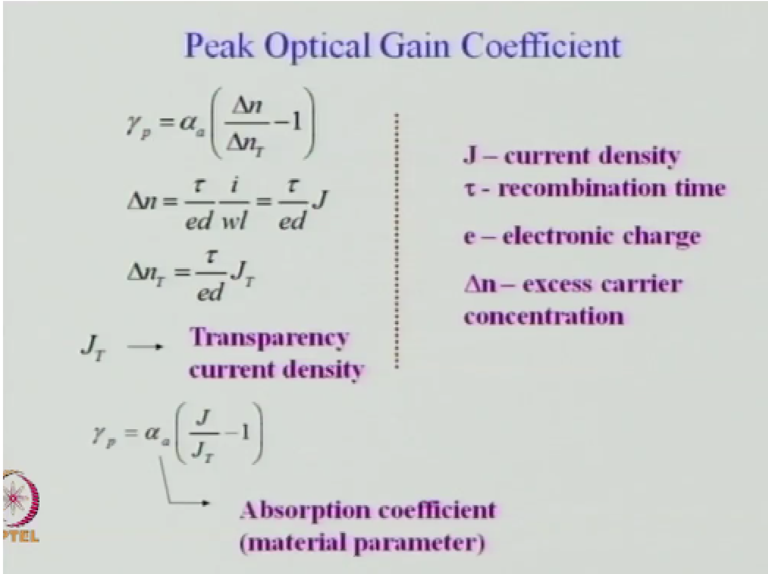

So, let us go to the peak gain coefficient, which is given by this expression here where delta n. So, let me erase this and keep only the expression because delta n is related to the current density. We have already derived this expression.

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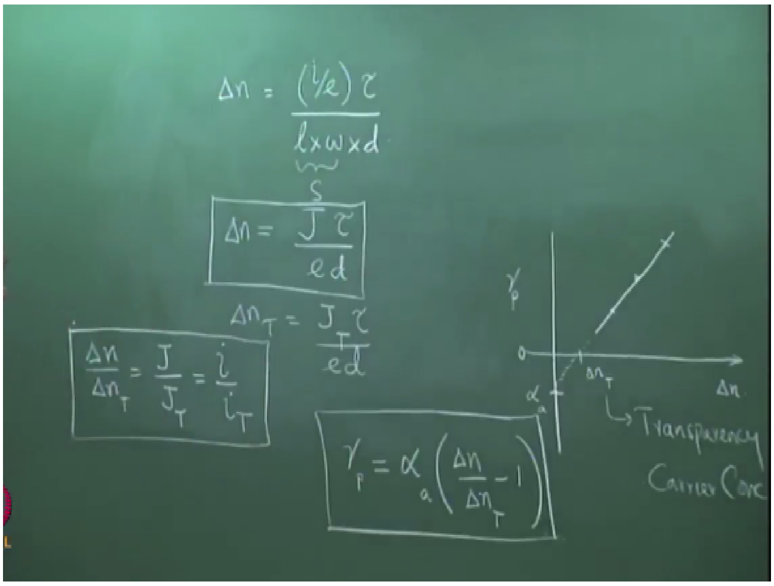

So, delta n here = I by e, we call that we had this expression divided by l into w into d. l into w into d. l into w into d, l is the length, w is the width. So, lw is the surface area and that is why we write this as S, so surface area S and I by S, current divided by S is J, so this is J into tau divided by ed. So, delta n = J tau ed and therefore delta nT here = JT, this is call the transparency current density into tau by ed.

So, normally one talks in terms of transparency current density. You could also write therefore you will see that delta n divided by delta nT = J divided by JT = I divided by iT.

Delta n divided by delta nT is J by JT all others cancel it is also equal to i divided by iT. So, iT is the transparency current through the device JT is the transparency current density and delta nT is the transparency carrier concentration. Is this okay?

So, all the parameters are defined again here and alpha a is the absorption coefficient.

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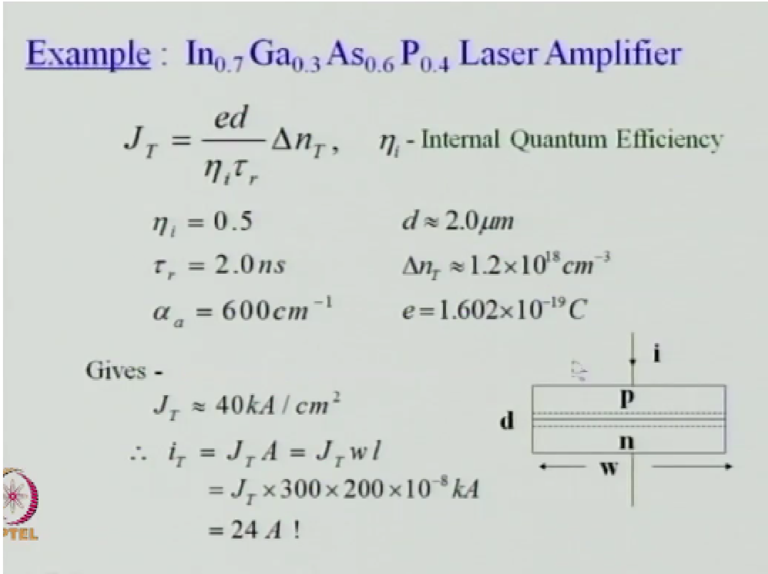

An example is given here this is from one of the books just taken as an example Indium Gallium Arsenide Phosphide laser amplifier JT the transparency current density is e into d by eta i into tau r there was tau, you recall that eta i by we had derived this expression eta i = tau by tau r. So, that tau has been replaced by eta i into tau in the denominator eta i into tau r because eta i is known for the material and tau are also is a measurable parameter.

You could have kept tau itself. eta i is typically 0.5, some numbers we have put. d is about 2 micrometer and tau r is of the order of nano second transparency carrier concentrations is given here delta nT because please remember it is delta n which will determine the separation between the Fermi levels. So, the separation between the Fermi levels should be such that you have to reach a situation where there is neither gain nor loss.

And therefore delta nT is the parameter for a given semi-conductor which will determine transparency. Alpha a is the absorption coefficient at that frequency typical numbers as you can see 600 centimeter inwards and e is the charge. So, if you substitute all these in this you get delta JT the transparency current density as 40 kilo amperes per centimeter square or the transparency current is this into A, A is l into w is the surface area A or S, I called S here.

So it is A, area here, so JT into A here refers to area. Actually I should I used to S. So, JT into w into l you substitute and you get 24 amperes what does that mean you have a diode through which you have to pass 24 amperes to reach transparency. You can imagine 24 amperes what kind of current it is, then air conditioner takes 10 to 12 amperes and a small diode taking 24 amperes.

It will simply burn off and this is exactly the reason although semiconductor laser was discovered in 1962. It never could operate on CW mode, continuous wave mode. They could show in pulse mode only. Because in pulse mode you can achieve the peak current of 24 amperes that is not a problem. Achieving peak current is not a problem. But average current or continuous current of 24 amperes the diode just cannot withstand.

And therefore for 8 years still 1970, from 1962 to 1970 all the semi-conductor lasers where only pulsed semiconductor lasers. There was no CW laser just because of this number. This number tells you that how can we achieve.

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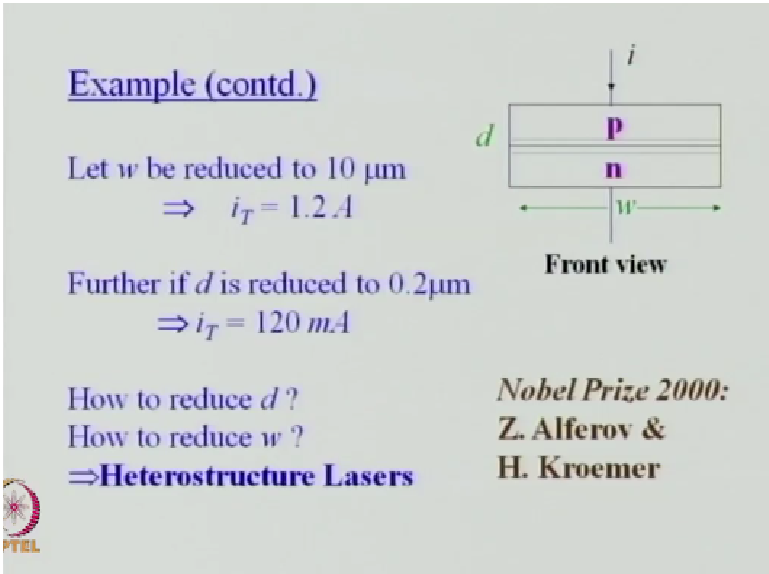

Now let us see further. therefore, how to bring this number to a reasonable order what are the possibilities. Suppose you reduce w that was the width if you see the front view the width, the width was 200 micron. Suppose somehow you reduce it to 10 micron which means a factor of 20. So, you have brought down the current from 24 amperes to 1.2 amperes because the factor of 20 w has been reduced. So, it is 1.2 amperes. You are now in a reasonable limit.

If you further decrease d, d for a normal PN junction, homojunction laser, homojunction PN junction it was about 1 to 2 micron. If you reduce it to 0.2 or 0.1 you get another factor of 10 and then the transparency current comes down to 120 million. This was the simple idea at an engineer's idea brought by Z. Alferov here who got finally the Nobel Prize in 1970. This has come and he got the Nobel Prize in physics in 2000.

I used to teach this course right from 1995 and always used to wonder what a nice idea this is. What a beautiful idea which led to and in 2000, he got Nobel Prize. So how to reduce d and how to reduce w. We said if we could reduce then it will work. So, how to reduce and this is by the use of Heterostructure.

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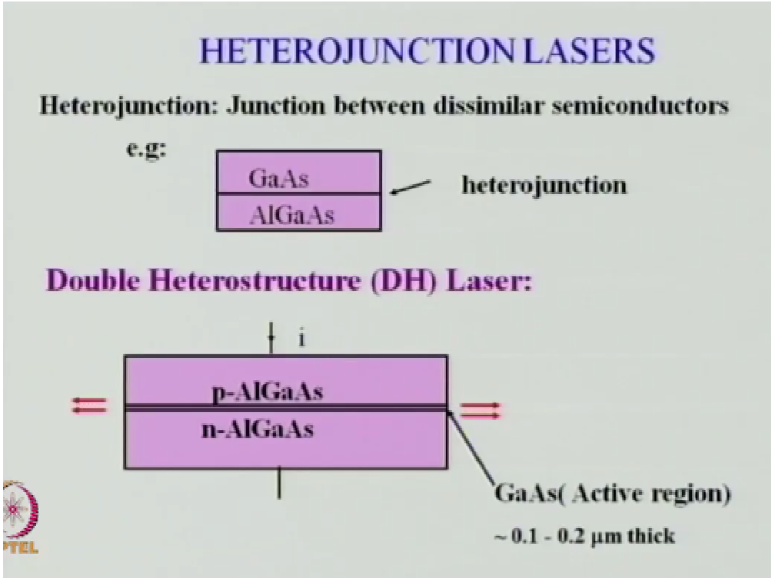

Some amount of discussion we already have had and here is Heterojunction lasers that brought into the picture Heterojunction lasers. Heterojunction refers to junction between dissimilar semi-conductors we have seen this and double Heterostructure laser the basic structure has a thin layer of Gallium Arsenide active region. Gallium Arsenide I have used as a typical material about 0.1 to 0.2 micron thick sandwiched between 2 layers of high band gap material which is Aluminum Gallium Arsenide for that material system.

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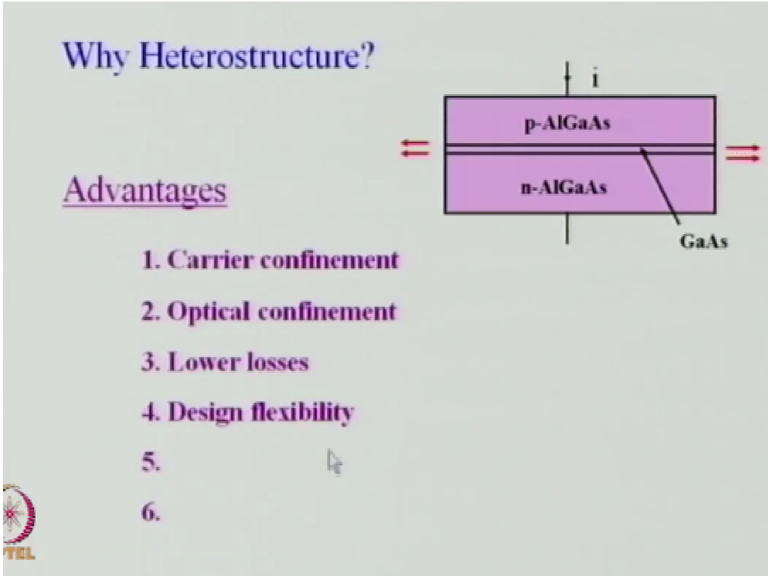

So, why Heterostructure some amount we have discussed the advantages are carrier confinement, optical confinement, lower losses, design flexibility. I have written 5 and 6 just left a cap because there are many more advantages. So, you can if you are interested you can find out but the first 3 are the basic advantages most important advantages. By design flexibility I mean for example I have listed here design flexibility.

You can take different compositions of x the alloy fraction. So, for example the basic structure although the basic structure is just this here.

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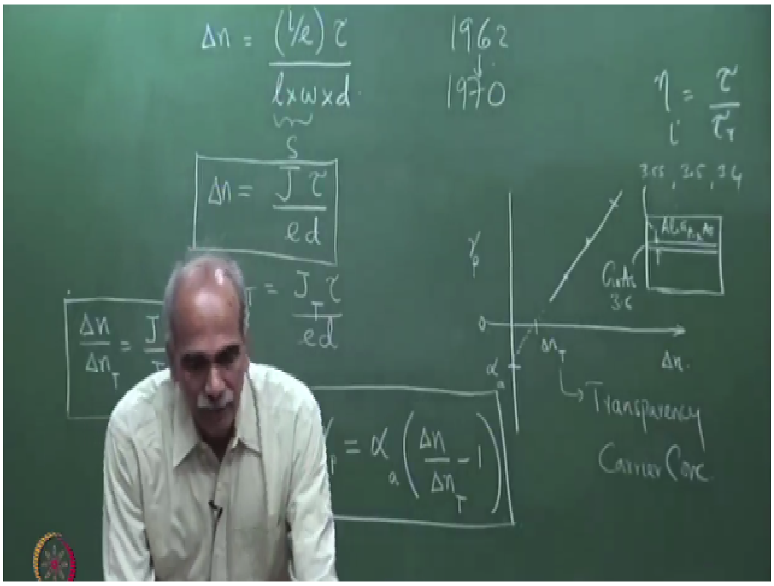

This material if you take Aluminum Gallium Arsenide, Al x Gallium 1 – x Arsenide and this is Gallium Arsenide. Please see that depending on the x fraction you will have different depths there + the refractive index this material has refractive index 3.6 depending on x this may have refractive index 3.55, 3.6, 3.5, 3.4 and so on depending on the value of x. So, what are you changing? You are changing n1 – n2.

Therefore, the confinement of the mode can be changed for a given thickness. You can also because of the double Heterostructure you have a provision of choosing 0.1, 0.15, 0.2 micrometer as the thickness. So, these are design flexibilities. So, this is what I meant by designs and there are many other advantages.

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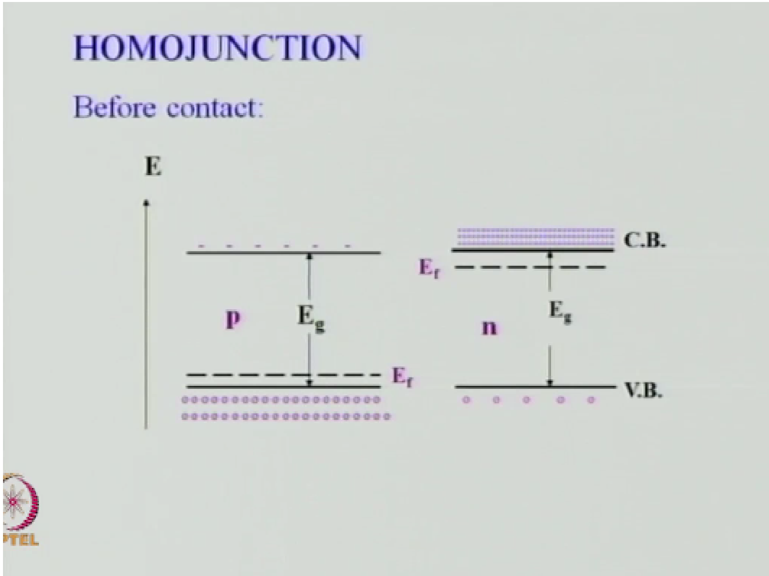

So, very quickly the PN junction diagram before contact in a homojunction. So, P and N no explanation is required.

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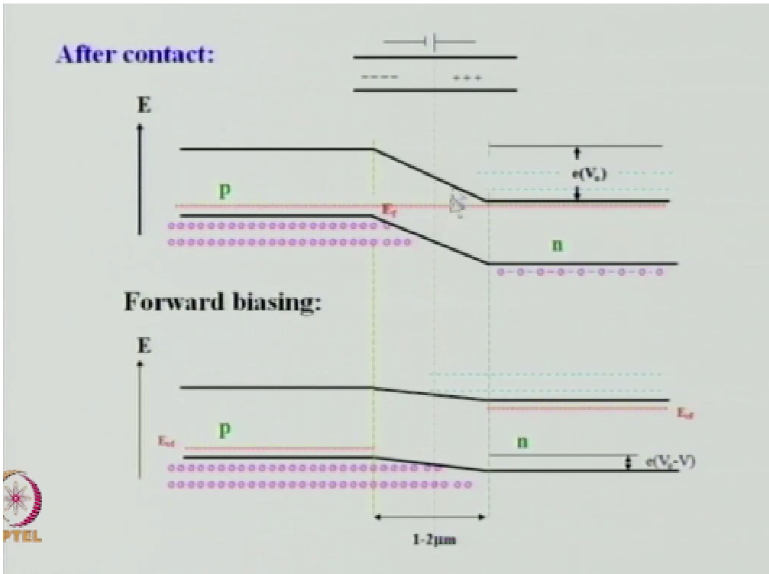

I suppose everything is clear there and after contact as we see before followed that we have 1 Fermi level throughout. This is the built-in voltage, built-in potential here and electrons are here, holes are here, plenty of holes. These circles, small circle represent holes and these represent electrons. But in the same position of X vertical this horizontal axis is X. Therefore, at a given position x in the junction region there are very little electrons and holes for recombination.

But when you forward bias the side of the band gets higher energy and therefore electrons move to this side, holes move on to the other side because the barrier is slower and therefore in the same position of X now you have plenty of electrons and holes available for recombination and generation of photons.

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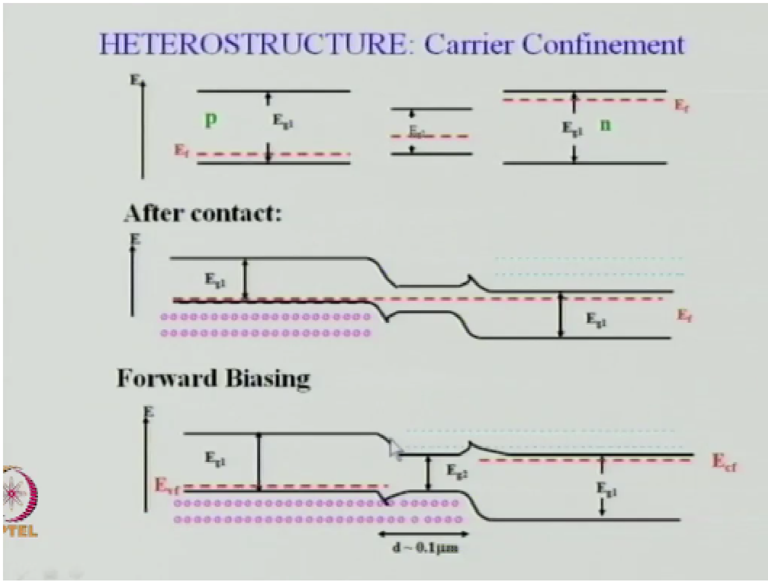

The point in the previous case is that the junction region, active region here is 1 to 2 micron thick and why going to heterostructure 2 things which happen is you choose d therefore 0.1 micron 0.15 micron you can choose. So, you are able to and because of this combination of high band gap and low band gap materials we have here potential barriers the electron when forward biased the electron comes to this active region yes but the barrier still exists on the other side.

So, the electron is forced to remain in this region, active region and similarly the holes are confined to the active region and the density, the concentration of carriers become extremely high for the same current because the volume where they are confined is very small. So, the carrier concentration is the carrier per unit volume becomes very high and it is delta n which will determine the separation between Fermi levels.

Therefore, as we discussed earlier given by passing a moderate current or a small current you are able to get now the separation between the Fermi levels very large.

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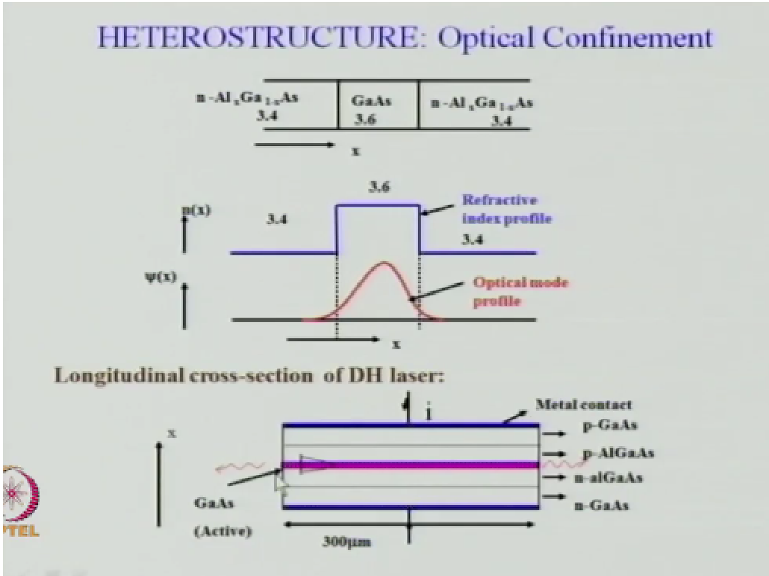

The second point, optical confinement. Again this is quite clear here these are the cladding layers which have lower refractive index. This is the active region here are the regions. So, this forms an optical wave guide which means it confines an optical guided wave which is an optical mode profile which shown here is more mode profile and this is the longitudinal cross-section of the laser.

So, if you see the longitudinal cross-section which means this is the length direction 300 micron shown here length and in the active region the mode propagates back and forth and at each end at each of these cleaved ends it undergoes partial reflection giving you the output. The remaining light acts as a feedback, optical feedback, alright.

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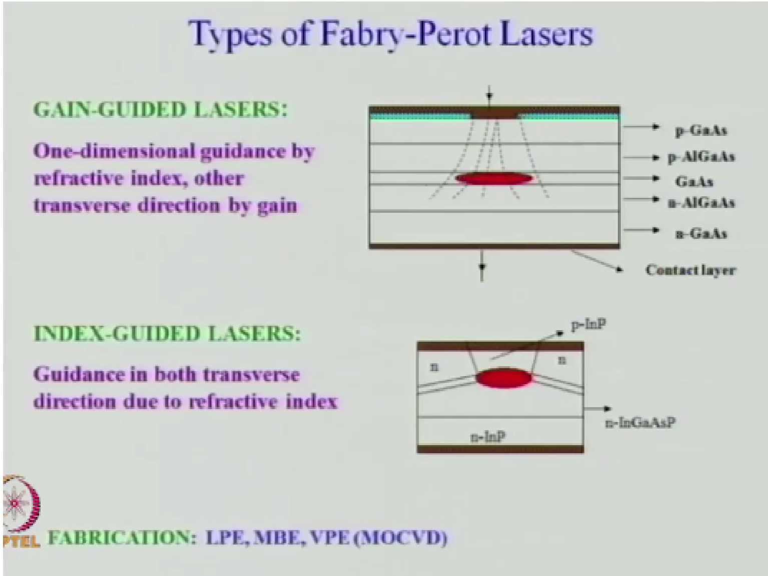

Types of Fabry-Perot lasers. They are broadly classified as gain-guided lasers and index-guided lasers. I have shown a typical structure of gain-guided and index-guided lasers. So, you can see that in a gain-guided laser as the name indicates the beam here is guided by the gain. This what is shown is the front view. So, this is the laser chip what is shown is the front view light is coming in this, okay.

So, the region is guided by gain what are you mean by that because the electrode here contact electrode here is restricted to a small region of about 5 to 6 micron the carriers primarily flow over a region of about 10 micron maybe 5 to 10 micron width and that means only in this region you have high carrier concentration which means only in this region you have high gain and therefore if you see this strip.

It is a strip all along the length and therefore the gain is confined to a strip all along the length which means the generated optical beam has to be confined only to that strip. There is no physical barrier, there is nothing which is physically confining but the gain is available only there. Therefore, the light builds up only under that contact electrode, contact strip and therefore this is call gain-guided laser.

The second one here structure as the name indicates is index-guided. So, that means you see there are different materials here. Here the refractive index is different, here it is different here it is different. So, the refractive index let me show you a, make it clear by showing a simpler structure.

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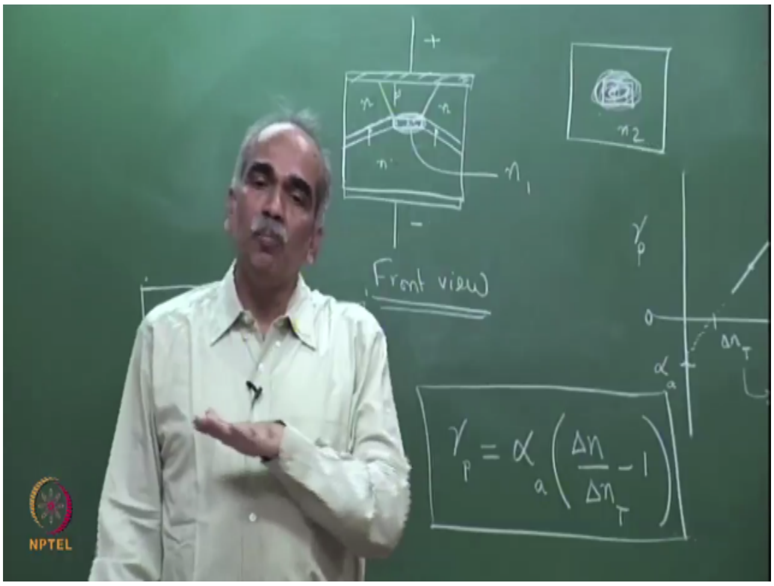

So, the structure is this, so what is shown there is a strip which is a rectangular strip here. So, this is p this is n. This is n and this is also n, sorry and in between so this is i and this region should be this region because I want this region to be reversed biased. So, you have a structure which has, so this is n this is n and this is p this region and this region is p please see. This is n p is the reversed biased.

You have applied positive here and you have applied negative here. So, only p n is the forward biased junction. This is reversed biased; this is forward biased but from here it is reversed biased. Therefore, the carriers have to flow through this active region, this is the active region and therefore light is generated in the active region. At the same time the materials are different here.

Therefore, you choose the refractive index such that this region has a refractive index n1 all around it has different refractive indices but less than n1. So, what is this strip, this strip please this is the front view as I have already mentioned front view. So, it is like this, front view. Which means all the region which is outside has refractive index lower compared to the active region and therefore this acts as an optical wave guide.

It is like fiber which has cladding everywhere or it is like a buried channel wave guide. For simplicity I will show you a rectangular wave guide like this which has n1 here and n2 everywhere. So light is confined only to this. So, you have light which is confined to the central region. Exactly like that light here generated is confined to the central region. What is confining? Refractive index difference and hence the name index-guided laser.

In the previous case it was in the previous case there is no refractive index barrier here. Light is confined to that strip because gain is available only under that. that is why it is gain-guided. Here it is index-guided. So, naturally you can see it to make such a structure the process steps involved are much larger. For the first structure gains-guided laser it is very easy. They are all simply monolithically deposited epitaxial layers. One layer on another, one layer on another.

Whereas, to make such a structure you have to use several processes of etching and regrowth. It is called etch and regrowth to achieve such a structure. Whereas in the gain-guided laser it is simply epitaxial layer deposition and therefore what would you expect the gain-guided lasers are much cheaper compared to the index guided lasers. For most of the commercial applications it is sufficient to use index-guided lasers which cost anywhere few Dollars or few 100 Rupees.

All the applications which they used for pointers and various applications it is a guided-laser which is used. Because you can fabricate in bulk very large numbers and very simple processes of epitaxial depositing layers required lasers. Whereas here you have to deposit layer you have to etch the required you have to have lithography to etch the required portions and then regrowth with another material.

And that is a and these cost at least 10 to 100 times more than gain guided laser. The cost of these are 10 to 100 times that of gain guided lasers. But where do you need this? Why do we go for such lasers? The field profile here, the field profile in a gain-guided laser depends on the current that is passing through. This is something important, this is an optical wave guide. The field profile is the profile of the mode of the wave guide.

The mode field profile is independent of the power. The optical power, the power means current you are passing initially let us say you are passing i = 10 milli ampere then you want to pass 50 milli ampere you want to get more power the beam will remain the same. Power in the beam will increase but the beam does not spread or it is field profile does not change because the field profile is determined by the optical wave guide.

It is the optical wave guidance which determines the field profile that is the transverse mode profile of the laser beam. Whereas in the case of a gain-guided laser see this now, it will become clear.

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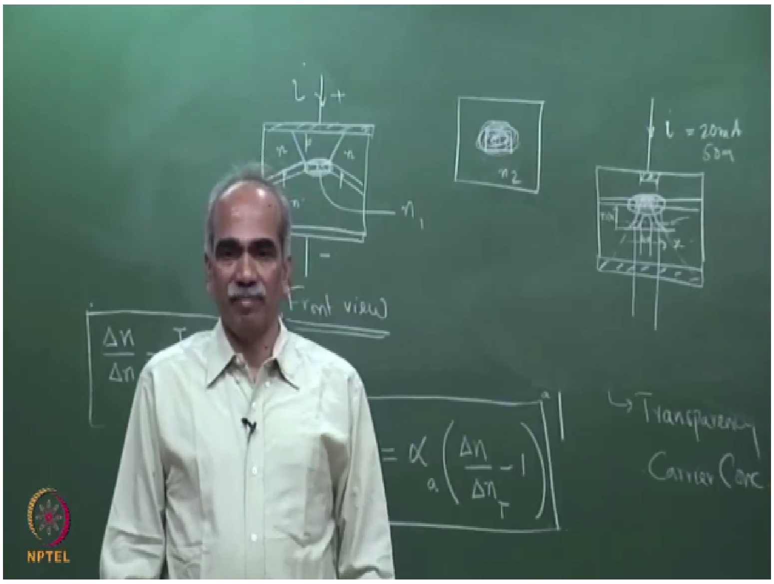

So, let me draw only that region, so you have the contact here. This is the active region and let us say the carriers flow is here and here is the field which is generated. In this direction it is guided it is a pnr slab wave guide but from the sides there is no confinement, no confinement from the sides. Everywhere it is front view, please remember always I am discussing about the front view means it is coming like this.

From the transverse side there is no confinement, so when I pass a current of I, i = let us say 20 milli ampere. Gain is available only over a small region here because the carrier concentration is sufficient to give gain in a small region. But so, if I want to show the carrier profile the carrier profile may look something like this, carrier concentration which is going but if I pass now 50 milli ampere and assume that his much, I hope you are able to understand.

This is the transverse direction, what I have shown is n (x) let say n (x) versus x and let us say this is the level required for having gain, the carrier concentration. If I now increase the current to 50 milli ampere the carrier profile will increase like this which means you see gain is up to this because the line is the same. The minimum carrier concentration required is the same. In this case within this region there was gain within this x value.

Now because my carrier concentration I am passing more current which means the carrier spread is more and therefore over a wider region we can expand this and we can expand this and see over a wider region there is gain which means this spot, size will become now bigger. You understand? If you pass a small current, then the beam profile is narrow because only in the central portion there is gain.

If you pass higher current the beam profile is spreading means what the profile of the beam intensity distribution here changes with current which does not happen here. There are applications where you do not want the field profile to change with current through the device. Current you are changing because you want to change the power. Here the field profile would change.

So, whenever you want an application where you want to maintain a constant field profile for example you want to use it in where you have to recall. You do not want the field profile to change but if your focus is only on intensity, intensity of the laser beams if you want to make use. You do not worry about the field profiles spreading or not you just want intensity there. You increase the current you want more intensity then it does not matter.

So, most of the consumer lasers are these ones that is why they are very inexpensive because you are making use of intensity and fast modulation capabilities of laser diodes. However, it is important to know because if you are a buyer of laser diodes working in some company like there is always specified index-guided lasers in the technical data sheet you will see index-guided or gain-guided.

Index-guided will be much more expensive and therefore depending on unless your application requires index-guided there is no point in buying index-guided, alright.

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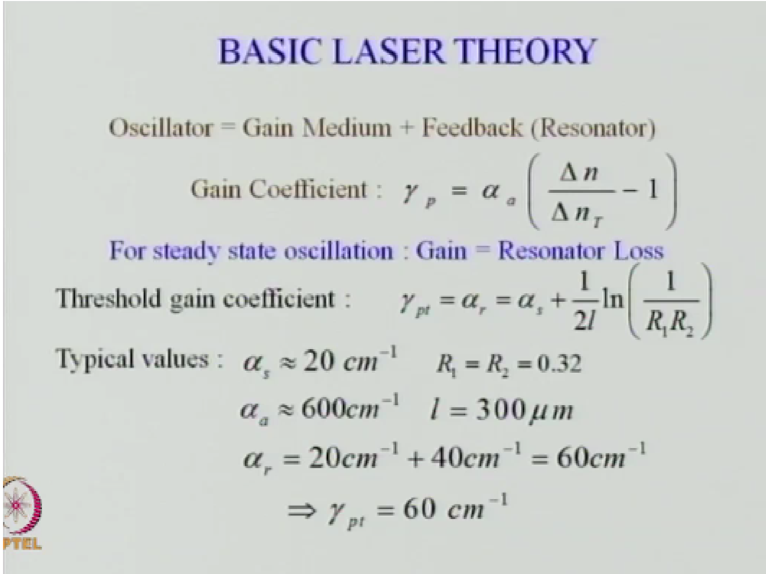

The basic laser theory, we briefly discussed yesterday. It is an oscillator; laser is an oscillator which means it gain + feedback. The gain coefficient, peak gain coefficient is given by an expression of this form. So, if you are looking at the peak the frequency corresponding to the peak gain if we equate this gain coefficient to the resonator loss, so that is what is written here.

For steady state oscillation gain = resonator loss which means at threshold this is gamma pt the peak gain coefficient at threshold is given by = the resonator loss which is here and substitute some typical values. Yesterday we have done some numbers and you see gamma pt is 60 centimeter inverse. Yesterday I have taken probably the same numbers, right. Typical numbers these are, alright.

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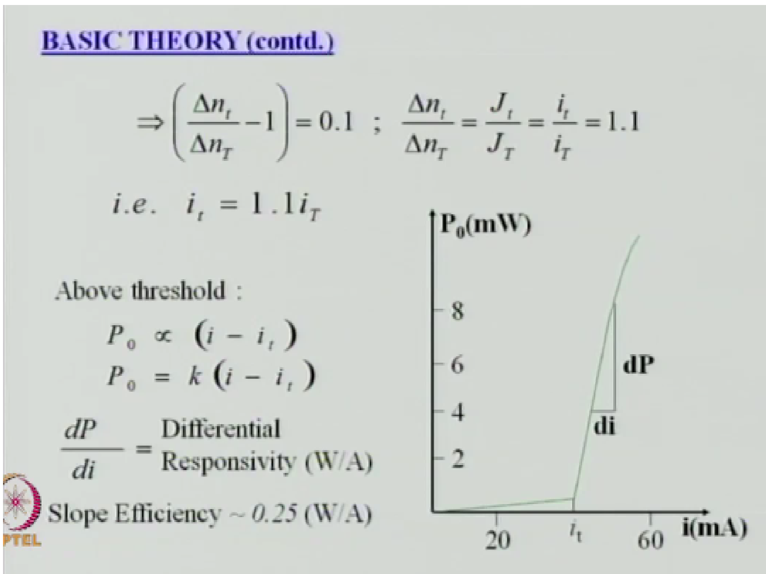

What we now bring the concept of threshold current. One is transparency current and the other is threshold current.

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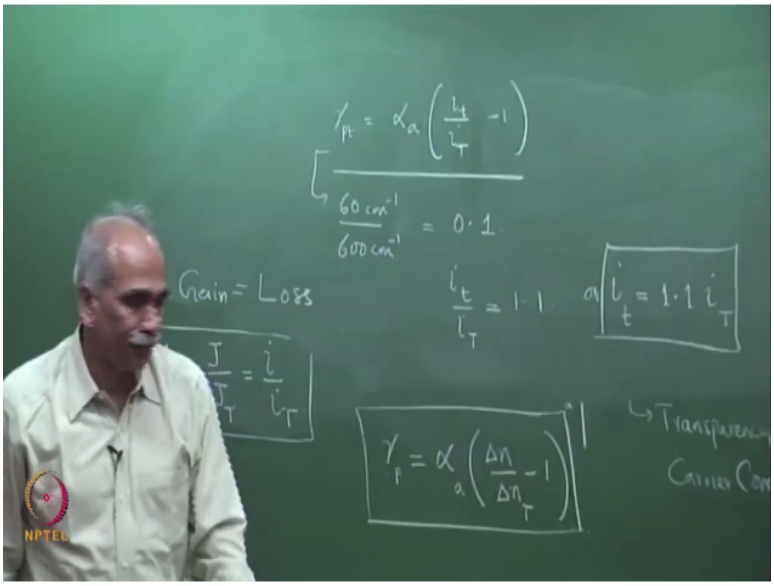

So, both are here, so you equate gamma p at threshold gamma pt = alpha a into delta n by delta nT. So, this is delta n by delta nT – 1. I can replace this delta n by delta nT by i and iT transparency because I have shown here it is i by iT because in a practical device you pass current your control is on current. So, i by iT – 1. So, this is the threshold current. How much is this threshold?

At threshold therefore we make i t the small t standing for threshold capitals T standing for transparency. How big is this? i t compared to this, so you can see some numbers are put there. We have this is 60 centimeter inverse, typical value alpha a is 600 centimeter inverse. There is a material loss coefficient, so this is = 0.1 alpha a by gamma p t which means i t, i threshold by iT – 1 = 0.1 or - 1 goes to the other side 1.1 or i threshold i t is = 1.1 times i t.

So, if you reach transparency current another 10% ahead if you go then you will reach the threshold current. Please see transparency current, see the clear distinction between the 2. Transparency current is the current when the medium is no more absorbing any current beyond that even if 1.001 times i t you will have gain. But the laser says there is a minimum gain required to compensate for loss.

And the threshold current corresponds to that minimum gain when you have gain = loss. So, gamma pt = loss, is this clear? And therefore the threshold current is always more than transparency current. This is when gain starts. This is when gain is = loss and therefore the threshold current is little higher than transparency current. So, beyond the threshold the power generated is proportional to the p optical is of the laser is proportional to this i – i T

Which means, so for i > i t. Because up to i t we need current to compensate for the losses in the resonated. Any additional current will give you additional optical power and therefore p optical is proportional to i - i T. It is the linear dependence and that is why you get the laser characteristic which is and here is the laser characteristic.

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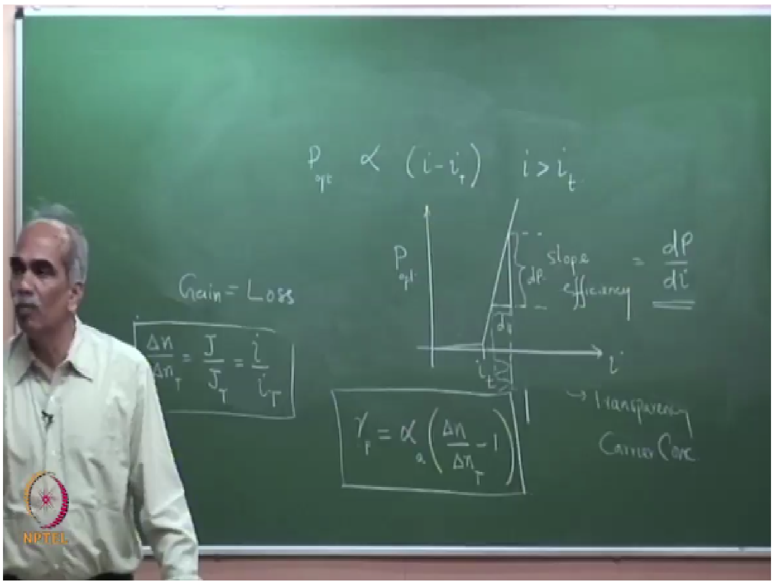

Therefore, you have i and p optical then there is hardly any output up to the threshold. There is some output which comes because of spontaneous emission. The laser is because of stimulated emission and here it starts. So this is the value where you have i t not transparency i threshold. It is the threshold current here, so typical practical lasers have 30-40 milli amperes as threshold current.

The laser diodes have 30 to 40 milli amperes, normal ones there are laser diodes which have threshold less than 1 milli amperes and there are laser diodes which have threshold much higher high current or high power laser diodes have threshold lead to higher. Normal ones have about 20 to 40 milli ampere.

So, this is the current variation that is described and in the in one of the classes I had mentioned that the laser output is characterized by slop efficiency or differential responsibility slop efficiency. Which is the change in power dP for a change in current di. So dP by di is the slop efficiency. This is = dP by di is called slop efficiency. You would like to have as high a slop efficiency as possible so that a very small modulating current here.

A very small excursion in a modulating signal here will lead to a large excursion in the optical power. So the slop efficiency is important for a modulation. So, typical numbers are given 0.25, 0.35 and so on. It is also called differential responsibility.

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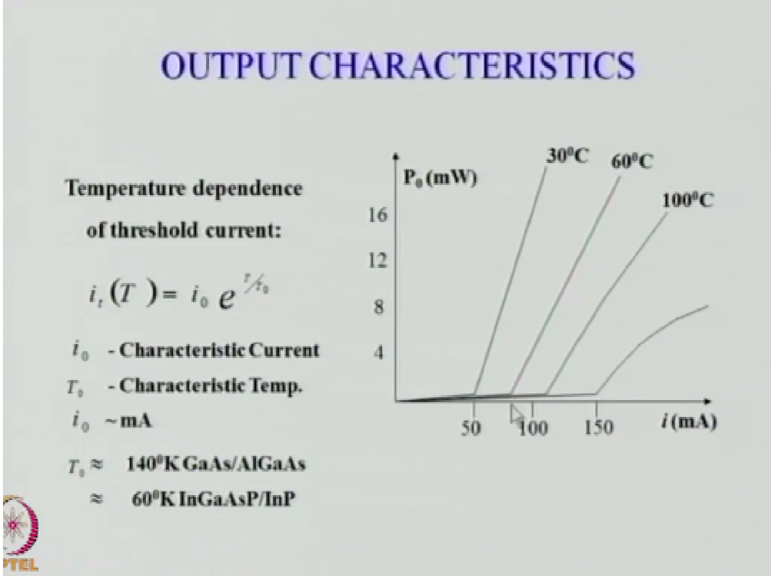

Output characteristic, so we come to the output characteristic. Earlier in the previous graph I had shown just 1 but here what is shown is output characteristic with the temperature and you can see that it is extremely sensitive to temperature. The threshold, which is here at the bottom, so here is the threshold. So at 30% if the threshold is 50 you see that at 60% it is increased to some 70 or 80 milli amperes.

So threshold is a strong function of temperature and therefore what it means what is its implication? Its implication is if you had biased here. Let us say, here at 75 milli ampere, okay in this diagram at 75 milli ampere reverse biased. Which means at 75 milli ampere it was giving some power here, optical power. Which is let us say, 10 milli watt. 10 milli watt at 75 milli ampere at 30 degree centigrade.

Due to some reasons the laser diode started getting heated. Slowly it is getting heated and if the temperature reaches 60 degree what happens the output is 0. There is nothing because the threshold itself is 80 milli ampere. So you had biased it at 75 but the threshold has become now 80. So the threshold is drifting with temperature. So laser diodes are very sensitive to temperatures and therefore laser diodes are always used with temperature controllers.

These are mounted on to the cooling elements to maintain a temperature. So laser diode drivers you will see that will always have temperature controller. Because you have to maintain constant temperature, if you want to use a particular characteristic. This is very sensitive. It is characterized by, so what is given is, here is an expression I hope you can see that i t the threshold as a function of temperature is i0 into e to the power i by i0, t by t0.

I am sorry, it is e to the power capital T by T0. T0 is called the characteristic temperature. This is a material property. So you can see some values of T0 are given it is 140k for gallium arsenide. Larger the value of T0 means less sensitivities for temperature. In fact, if you use quantum well lasers, the T0 is very large for quantum well lasers. They are much less sensitive to temperature variations.

Typically, 350-375 degrees is the T0 value for quantum well structures. Whereas Indium Phosphide Lasers are more sensitive here and you can see it is T0. So this is the relation we tell you how the threshold is shifting with temperature. Why is it shifting? Good question. Find out the answer. Why do you think that it is shifts with temperature? Primary reason of course is with temperature tau the recombination time drops rapidly.

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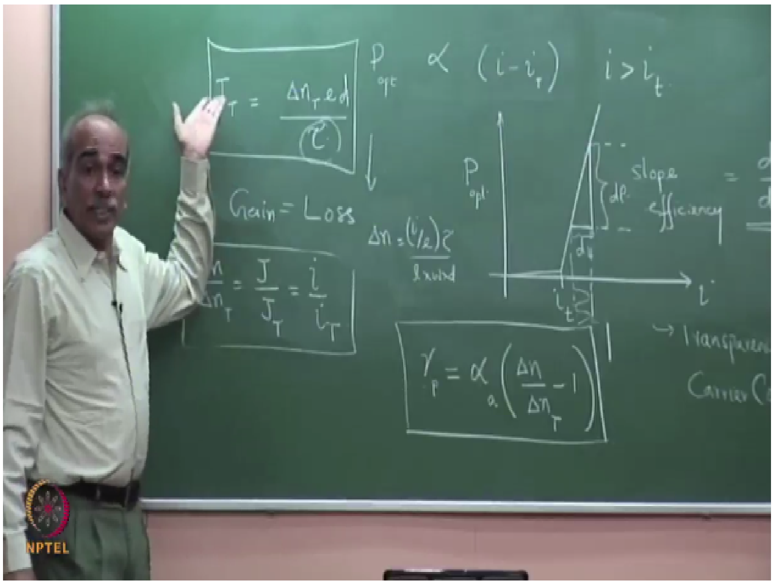

And tau drops rapidly means you see there is tau somewhere, where is tau? In the expression for delta nT we have in the expression for JT the transparency current density drops down rapidly. JT = delta nT this is a parameter to get the required separation into so we had e into d divided by tau. We had delta n = alright. Delta n, we see we had this expression delta n = i by e into tau divided by l into w into d.

So I by lw is J, so Jd and therefore JT = so this is J into therefore this tau drops down rapidly with temperature. The carrier recombination drops down very rapidly because of non-radiative recombinations. and transitions and if this drops down transparency goes up. The transparency current density and therefore the threshold will go up. So iT goes up JT or iT goes up and threshold is about 10% or20% more than the transparency and therefore the threshold current will go up. This is the primary reason why the current goes up.

So, we will stop here at this point and in the next class we will take up output characteristics, device characteristics, various spatial profiles, wave length profile, spectrum and so on.