Semiconductor Optoelectronics
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Lecture - 34
Semiconductor Laser -1 Device Structure

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

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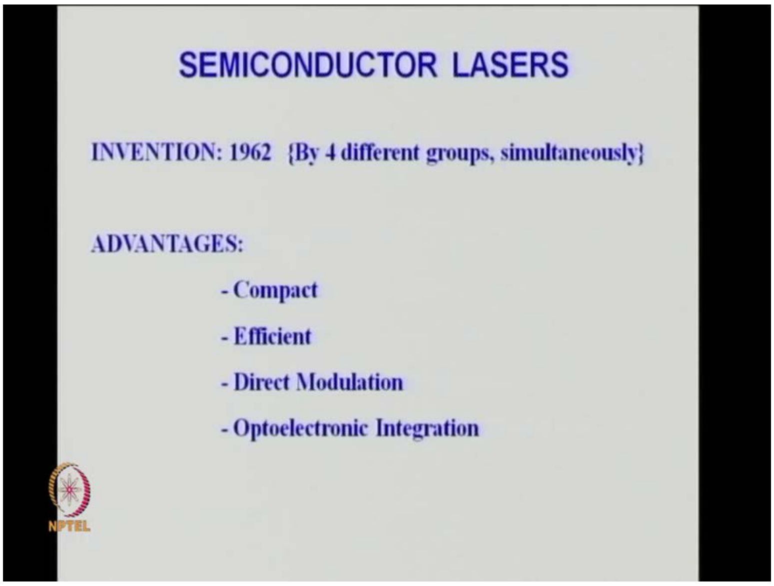

So, usually one does not assign credit to anyone group, but the main advantages of semiconductor lasers are: they are compact. You already know the size that is involved is very small. A helium neon laser with about one foot long is about five mile watt of power, a small semiconductor laser can give you 100 milli watts of power is very compact and very efficient. Efficiency is measured in terms of power conversion efficiency is very efficient, a normal bulk lasers have efficiencies between 0.1 to 1 percent normally, except firly 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, efficiencies normally are 20 to 30 percent electrical to optical conversion, and there are devices people have shown efficiency in excess of 60 percent that is just consuming 2 milli watt of power and a electrical power 2 mile watt which is very low and giving 1 milli watt of optical power that is really very efficient.

The other important characteristic, why semiconductor laser is used in communication and all the consumer applications is the possibility of direct modulation. Most of the bulk lasers modulation here we refer to any signal or any communication is send through modulation though most of the bulk lasers you use the laser output and put an external modulator here.

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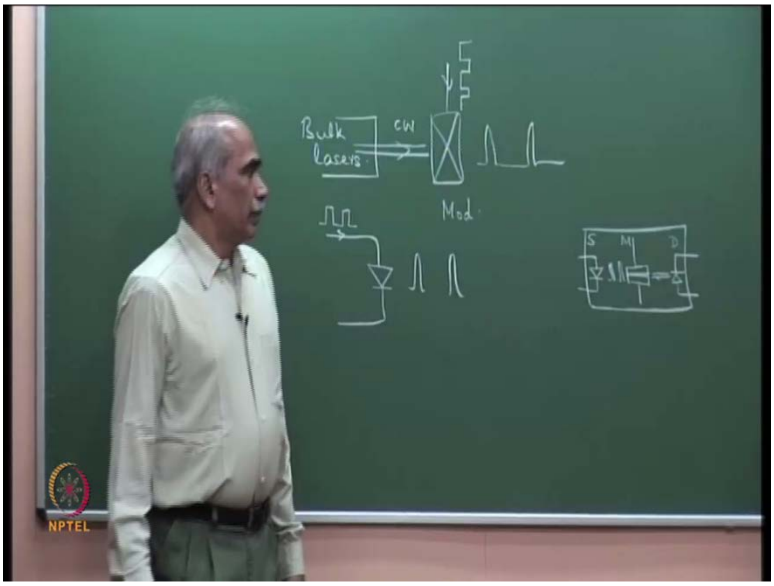

So, this is an external modulator. Whereas, in semiconductor laser are most practical purposes, except when the speed involved is more than several Giga bit per second it is sufficient you can directly modulate you simply bias the modulation current here, bias the diode current by the modulating signal and you will get accordingly the output. So, this is called direct modulation that is the modulating signal is directly superimposed on the diode bias current. Whereas in bulk lasers, you usually have a C W output here continues wave output and the modulator then biases, modulator then modulates with the required. So, you feed the modulating signal here on to the modulator.

The modulator takes input the digital input or the modulator bit pattern is fed to the external modulator and whereas, in the case of semiconductor lasers direct modulation and this is very helpful it saves use of 1additional component 1 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 schematically 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 a 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 component on a chip are not very large, a few components only 4 6 8 not more than that normally on a whereas when you talk of a VLSI or micro electronics, we are talking of millions of components on a chip.

So, we do not have that kind of numbers, but never the less you can integrate some of the active devices and components on a single chip. This is what we refer to as optoelectronic integration.

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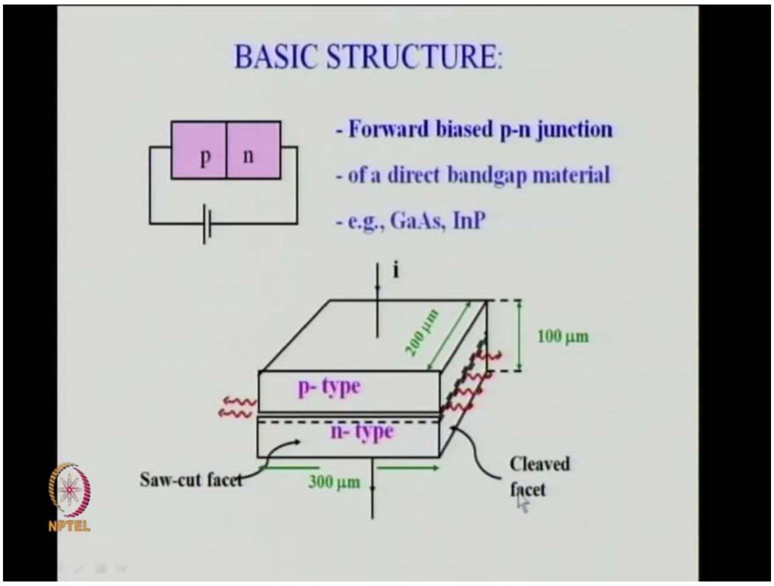

The basic structure of a semiconductor laser is as we have discussed in detail it is a forward biased p-n junction here is a forward biased p-n junction, and made of a direct band gap material such as gallium, arsenate, indium phosphate, we have discussed in enough detail, but I would like you to see the structure here what is shown with a 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 two cleaved facets yesterday I mentioned about cleaved facets acting as mirrors at the two 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 two ends which are here and on the other side that is this facet and on the back side here or 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 two sides there is rough surface otherwise, light could as well have built up in this direction like ,this it could have gone bracken from in this direction which means light could have come from here that is from this output here.

So, you want like to come in from a particular direction and therefore, two sides are saw-cut the other two sides are cleaved.

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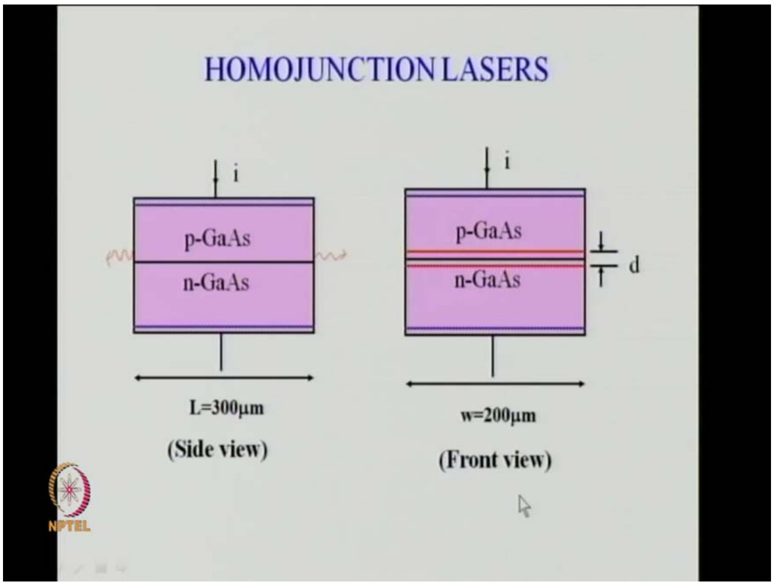

So, that resonator is formed in that direction and current flows through the device originally when it was discovered in 1962 they where homo junction lasers that is simple p-n junctions, highly doped p and n materials forming a p-n junction and the depletion region or the active region here, as a thickness of approximately d which is typically 1 to 2 micron in a p-n junction and this is the front view. The width is about 200 micron, the side length is about a 300 micron as we saw in the previous slide.

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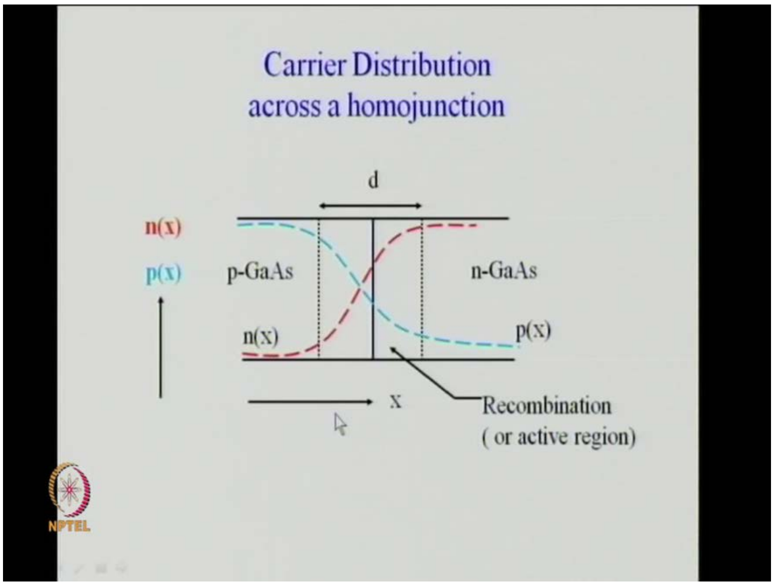

The carrier distribution across the junction these are basics which we have already discussed in detail. So, let me quickly go through them the carrier distribution across the junction you shown here. So, this is a n(x) here, the carrier density across the p-n junction this is x direction. So, p side and n side here p is the majority carrier and it drops down across the junction and this is our recombination region or the active region, very quickly recalling.

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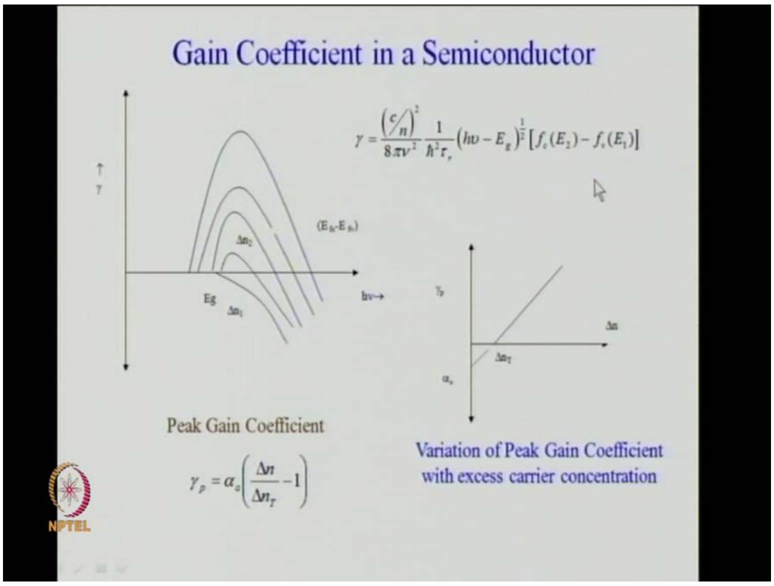

Now let us see this gain coefficient in a semiconductor we have got this expression for gain coefficient. I hope those of you had a back or able to read it as a little small, but I wanted to show the two figures from the same diagram some discussions some explanation is required here.

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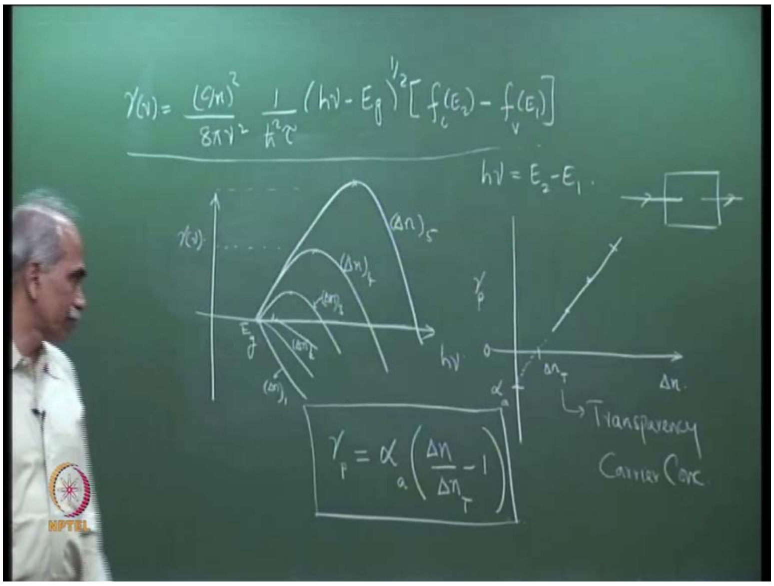

We have got this a expression for gain coefficient gamma is equal to c by n whole square 8 pi nu square into 1 over h cross square tau r h cross square tau into h nu minus E g actually h cross square tau we had used tau there.

So, let me not write tau r h cross square tau h nu minus e g to the power half into that is f g last 1 is f g that is f c of E 2 is in queasy equilibrium and f v of E 1 E 2 is a level such that, this is for gamma of nu gain coefficient gamma of nu and E 2 and E 1 are such that h nu is equal to E 2 minus E 1. So, all the quantities in this expression we know and this if you plot for different energies. This is what we have already plotted which is here when you are in the last class also we have discussed this is h nu and this is gamma gamma of nu this point is E g is it alright, h nu gamma of nu versus h nu.

So, this is for different values or these are for different values of delta n, now this is the plot for the active medium the peak in coefficient here gamma p gamma p gamma p here. So, these are the peak in coefficient corresponding to various values of delta n. So, if you called this as delta n 0 now delta n 1 delta n 2 delta n 3 this is delta n 1 2 is not delta n 1.

So, various values of delta n delta n 3 delta n 4 and delta n 5 there are different values of gain coefficient here, the peak gain coefficient if you plot this gain coefficient and second curve what it shows 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 semiconductor is in there is no excess carrier concentration which means they 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 0. So, the value of delta n at which the peak gain coefficient please see there is no peak here.

So, if I take this particular delta n here you can see that the peak is just 0 for this value of delta n I am when the transition takes place from negative side to positive side there is it place where is the peak is said 0 and that value of delta n is called the transparency carrier concentration delta n T. Capital T standing for transparency.

So, transparency carrier concentration 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 is equal to alpha a into delta n minus by delta n T minus 1. You can see this when delta n is equal to delta n T gamma p is 0 and when delta n equal to 0 it is minus alpha a.

So, here alpha a this is the equation of the straight line, if approximately a straight line is not any theoretical s 1. So, it happens that its approximately a straight line, but this can be used a reasonably with a good approximation gamma p is equal to alpha a into delta n minus delta n T please recall the delta n T 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 as like as we if it is transparent, there is no absorption no amplification means what is transparent is no change in the intensity. So, you have a medium here and if this is transparent whatever is input goes output. So, either amplification nor absorption thus, why the name transparency carrier concentration delta n T. So, this a slide is a clear there.

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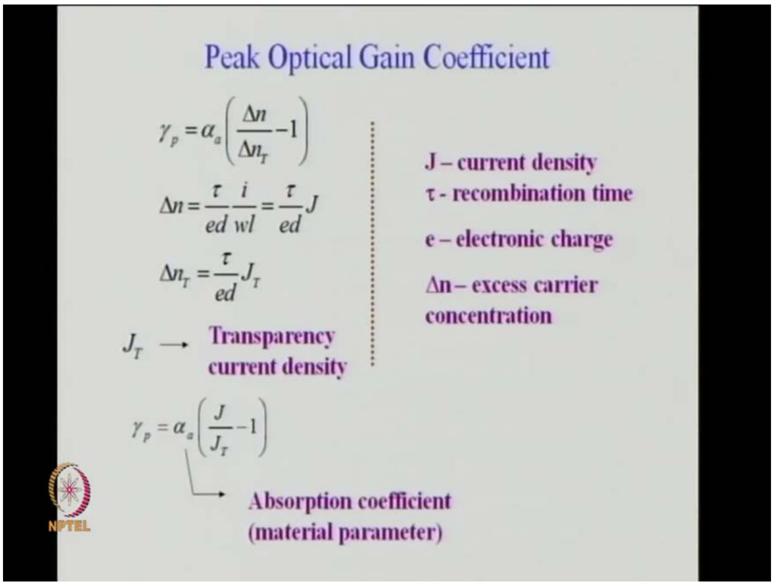

So, let us go to the peak gain coefficient which is given by this expression here, where delta n, let me read this and keep only the expression because delta n is related to the current density we have already derived this expression.

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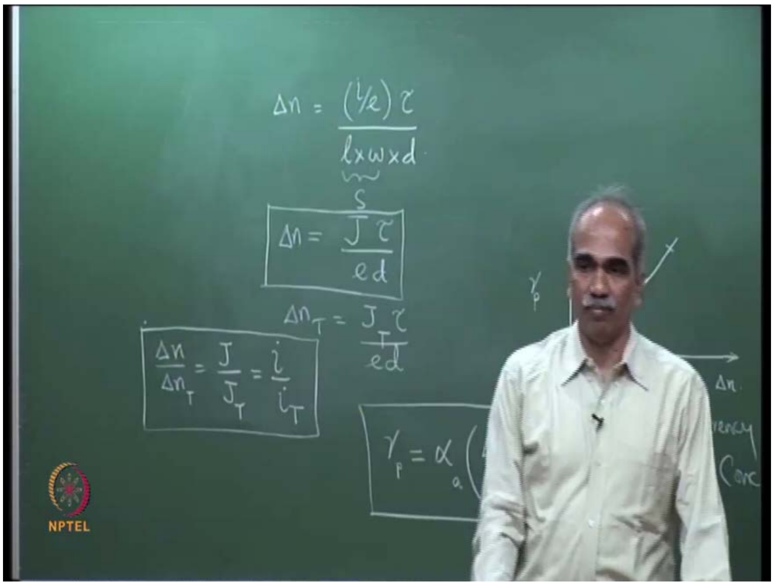

So, delta n here is equal to i by e recall that we had this expression divided by l into w into d. l into w into d l into w into d l is the length, w is the width. So, l w is the surface area and that is why we write this as s surface area s and i by s current divided by s is J. So, this is J into tau divided by e d. So, delta n is equal to J tau e d. And therefore, delta n

T here is equal to J T this is call the transparency current density into tau by e d. So, normally one talks in terms of transparency current density. You could also write therefore, you will see that delta n divided by delta n T is equal to J divided by J T is equal to i divided by i T delta n divided by delta n T is j by J T all others cancels it is also equal to i divided by i T. So, i T is the transparency current through the device. J T is the transparency current density and delta n T is the transparency carrier concentration this is.

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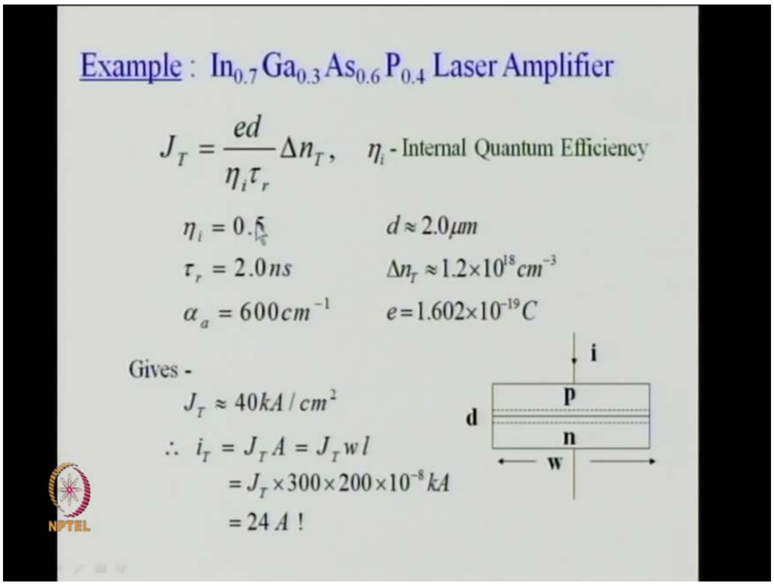

So, all the parameters are defined again here and alpha a is the absorption coefficient an example is given here this is from one of the books just taken as an example indium, gallium, arsenate phosphate laser amplifier. J T the transparency current density is e into d by eta i into tau r there was tau you recall that eta i by we had derived this expression eta i is equal to tau by tau r.

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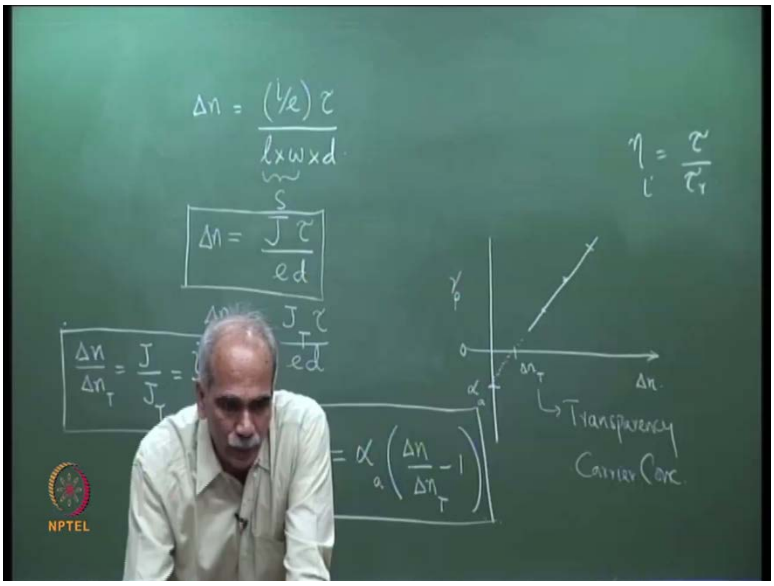

So, that tau has been replaced by eta i into tau in the denominator eta i into tau r because eta i is known for the material and tau r also is a measurable parameter. You could have kept a tau itself eta i is typically 0.5 some numbers we have put d is about 2 micron meter and tau r is of the order of nano second transparency carrier concentration is given here delta n T 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 the situation where is neither the gain nor lose. And therefore, delta n T is the parameter for a given semiconductor which will determine transparency alpha a is the absorption coefficient at that frequency typical numbers as you can see 600 centimeter inverse and e is the charge.

So, if you substitute all these in this you get delta J T the transparency current density is 40 kilo amperes per centimeter square and 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, J T into A here refers to area actually I should I have used to s. So, J T into w into l you substitute and you get 24 amperes are does z me you have a diode through which we have a pass 24 amperes to reach transparency you can imagine 24 amperes what kind of current it is than air conditioner takes a 10 to 12 amperes and a small diode taking 24 amperes it will simply burn of and this is exactly the reason although semiconductor laser was discovered in 1962. It never could operate on C W mode continues wave mode they could show lasing in pulse mode only.

Because in pulsed mode you can achieve the peak current of 24 amperes does not a problem, achieving peak current is not a problem, but average current or continues current of 24 amperes in the diode just cannot withstand.

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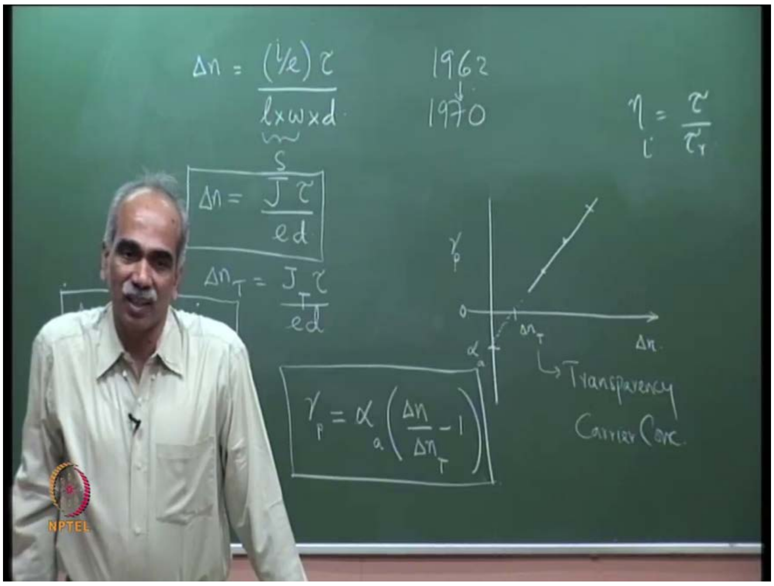

And therefore, for 8 years still 1970 from 1960 to 19 1960 to 1970 all the semiconductor lasers where only pulsed semiconductor lasers there was no C W laser just because of this number, this number tells you that how can, we achieve lasing.

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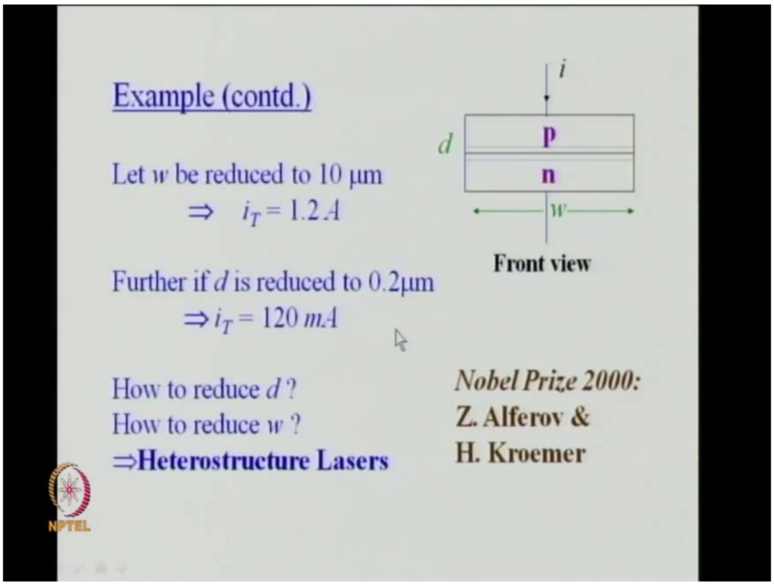

Now let us see further therefore, how to how to bring this number to a reasonable order what are the possibilities.

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 drop 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 decreased d d for a normal p-n junction homo junction laser homo junction p-n 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 mile ampere. This was the simple idea at an engineer's idea brought by Z Alferov here.

Who got finally, the Nobel prize in 1970. This was this as come and he got a Nobel prize in physics in 2000. I used to teach this course write from 1995 and always used to wonder what is an nice idea this is, but a beautiful idea which will relate to and in 2000 he got a Nobel prize. So, how to reduce d and how to reduce w we said if we could reduced then it will work.

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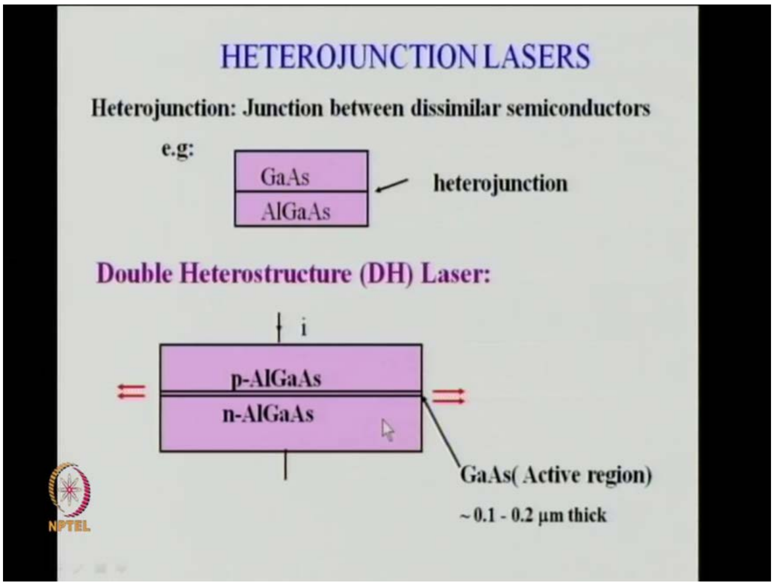

So, how to reduce and this is by the use of hetero structure some amount of discussion. We already have add and here is hetero junction lasers that brought into the picture hetero junction lasers hetero junction refers to junction between dissimilar semiconductors we have seen this and a double hetero structure laser. The basic structure has a thin layer of gallium arsenate. Active region gallium arsenate have used as a typical material about 0.1 to 0.2 micron thick sand witched between two layers of high band gap material, which is aluminum gallium arsenate for that material system.

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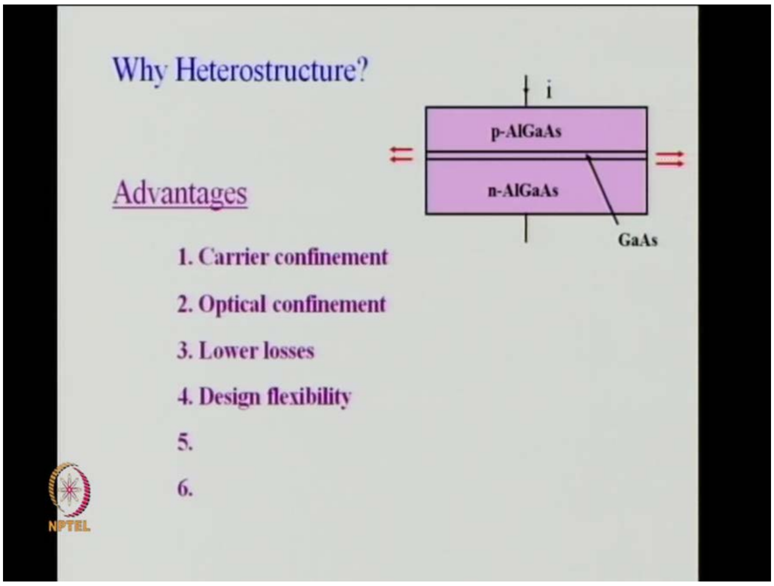

So, why hetero structure some amount we have discussed. The advantages are carrier confinement optical confinement lower losses design flexibility I have written 5 and 6 just left a gap there are more advantages. So, you can a if we are interested we can find out, but the first 3 are the basic advantages. 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.

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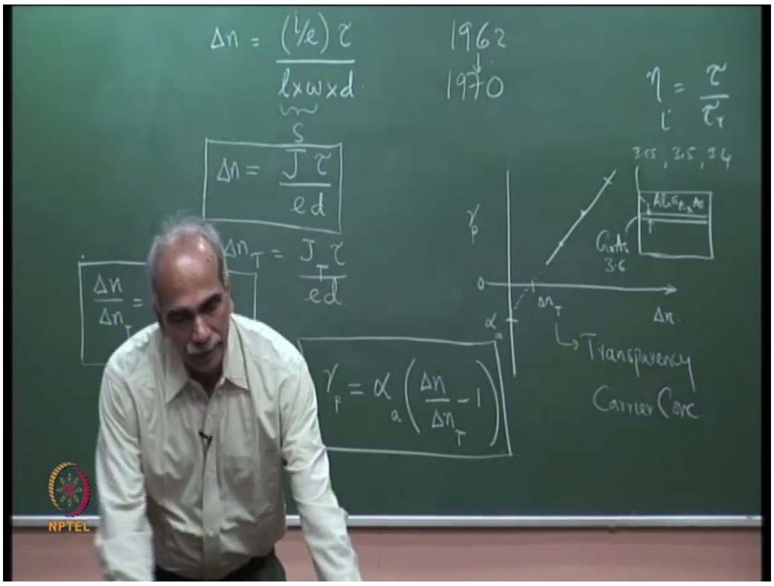

So, for example, the basic structure although the basic structure is just this here this material if you take a aluminum gallium arsenate A l x gallium one minus x arsenate and this is gallium arsenate please see that depending on the x fraction you will have different depths there plus the refractive 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 change you are changing n 1 minus n 2 therefore, the confinement of the mode can be changed for a given thickness, you can also because of the double hetero structure you have a profession of choosing 0.1, 0.15, 0.2 micro meter as the thickness. So, these are design flexibilities. So, this is what I meant by design and there are many other advantages.

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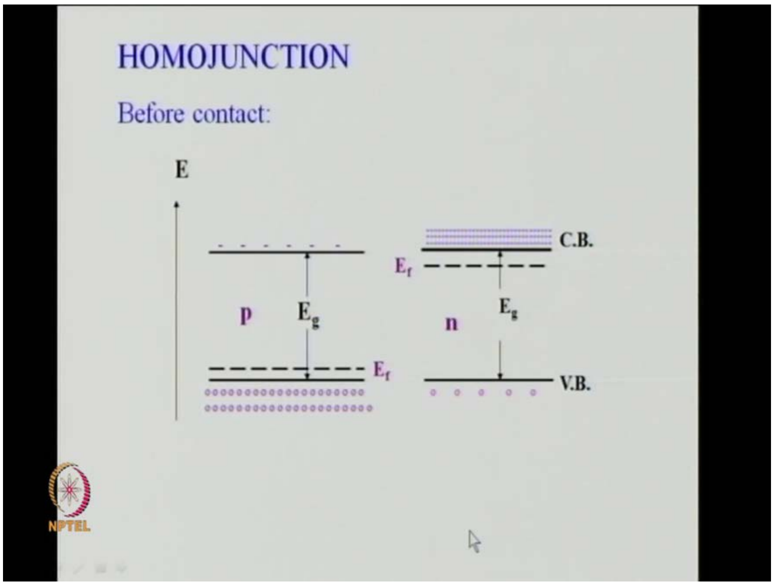

So, very quickly the p-n junction diagram before contact in a homo junction. So, p and n no explanation is required. I supports everything is clear there.

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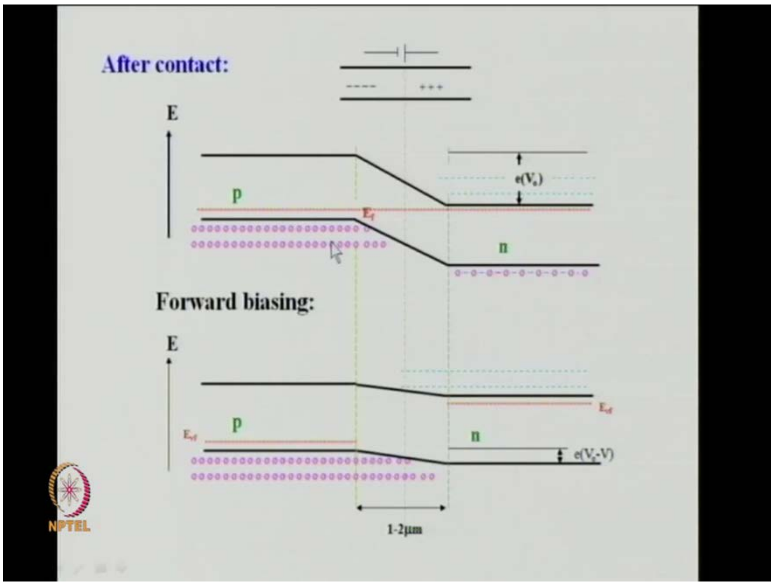

And after contact as we see before forward biasing we have one Fermi level throughout. This the built in voltage will take potential here , and a electrons are here, holes are here, plenty of holes these are circle small circles represent holes, and these represent electrons, but in the same position 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 of the barrier is lower and therefore, in the same position of x now you have plenty of electrons and holes available for recombination and generation of photons. The point in the previous case is that the junction region, active region here is 1 to 2 micron thick.

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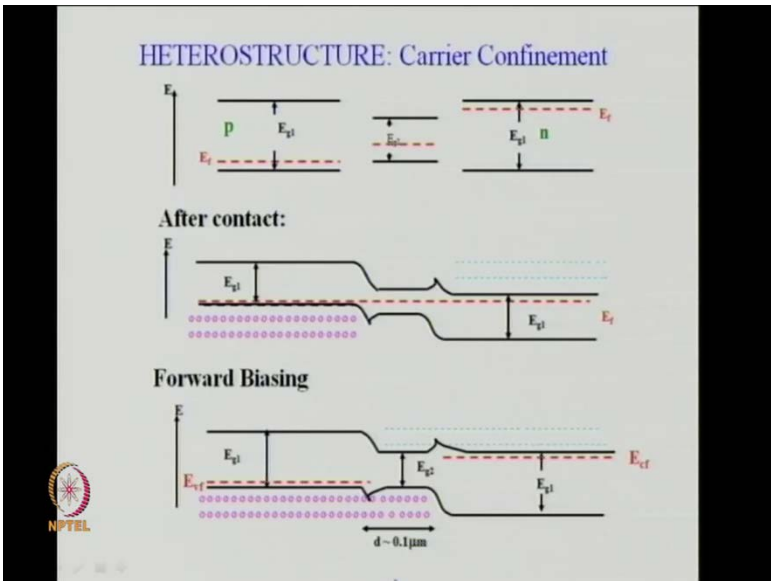

And why going to hetero structure two things which happen which you choose d therefore, 0.1 micron 0.15 micron you can choose, you are able to and because of this combination of high band gap and low band gap materials we have here, potential barriers the electron went forward bias the electron comes to this active region s, but the barrier still exist on the other side.

So, the electron is force 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 the Fermi levels therefore, as we discussed earlier even 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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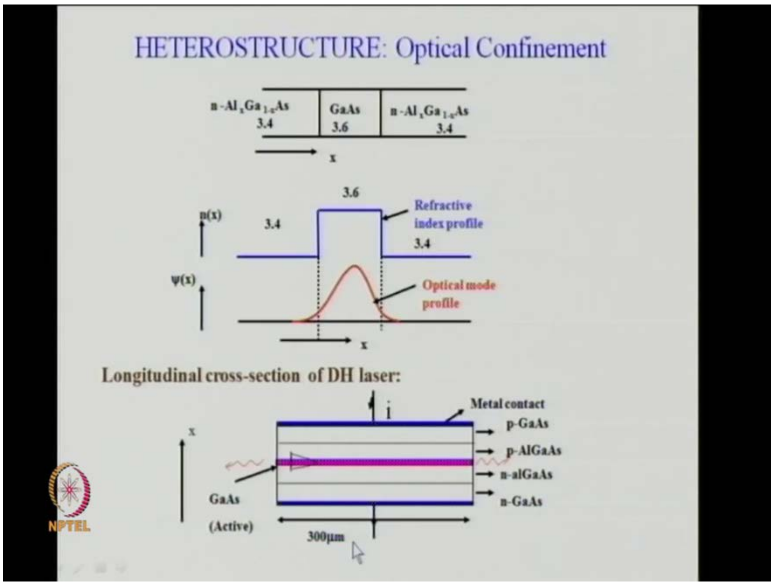

The second point, optical confinement again this is quite clear here this is this are the cladding layers which have lower refractive index this is the active region, here are the regions. So, this forms an optical wave guide which means it confines an optical guided wave which is an optical mode profile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

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

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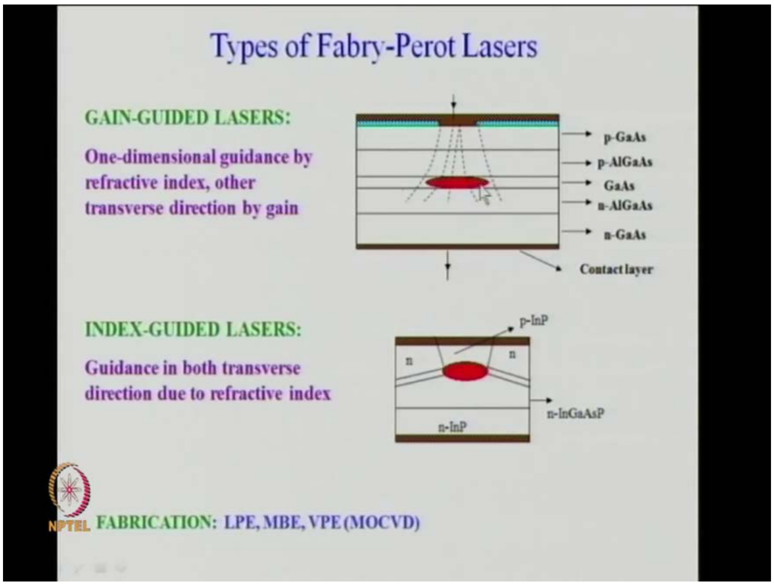

Types of Fabry - Perot lasers they are broadly classified as, gain guided lasers and index guided lasers. I have shown a typical structure of gain guided and index guided lasers. So, you can see that in a gain guided laser, as the name indicates the beam here is guided by the gain this what is shown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

So, the region is guided by gain what do you I mean that, because the electrode here contact electrode here is a restricted to a small region of about 5 to 6 micron the carriers primarily flow over a region of about ten micron may be 5 to 10 micron width and; that means, only in this region you have high carrier concentration which means only in this region to have high gain and therefore, if you see this strip it is a strip all along the length and therefore, the gain is confine to a strip all along the length which means the generated optical beam as to be confined only to that strip there is no physical barrier.

There is nothing which is physically confined, but the gain is available only there therefore, the light builds up only under that contact electrode contact strip and therefore, this is called gain guided laser. The second one here structure has the name indicates is index guided so, that means, you see the there are different materials here the refractive index has been 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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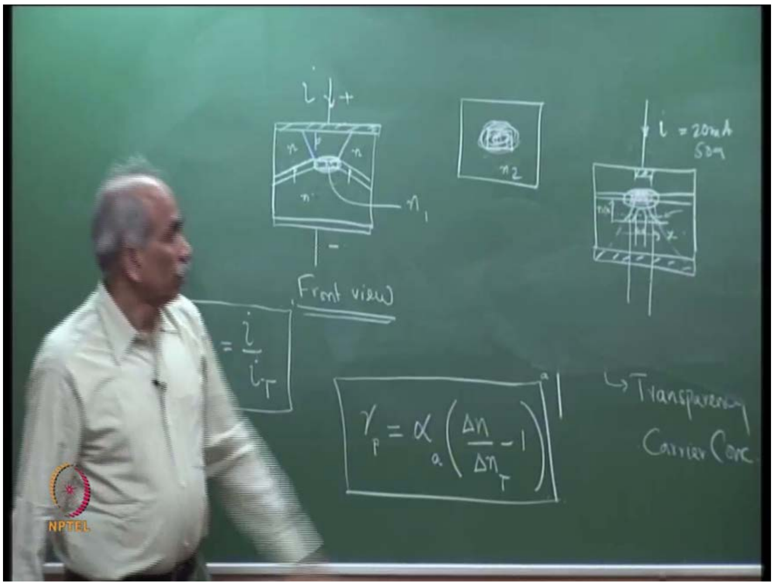

So, the structure is this. So, what is shown there is a strip which is a rectangular strip here. So, this is p this is n this is n and this is also n and in between. So, this is I and this region I should be this region because I want this region to be reverse biased. So, you have a structure which has this is n this is n and this is p this region and this region is p please see this is n p n p is the reverse biased you have applied positive here and you have applied negative here.

So, only p n is the forward biased junction. This is reverse biased this is forward biased, but from here it is reverse 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 n 1 all around it as different refractive indices, but less than n 1.

So, what is this strip? this strip please see 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 compare to the active region and therefore, this acts as an optical waveguide.

It is like fiber which has a cladding everywhere, or it is like a berried wave guide for simplicity I will show you a rectangular waveguide like this which has n 1 here and n 2 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 the fractive index difference and hence the name index guided laser in the previous case it was in the previous case there is more refractive index barrier here light is confined to that strip because gain is available only under that that is why it is index guided I have that is why it is gain guided here it is index guided. So, naturally you can see to make such a structure the process steps involved are much larger.

For the first structure gain structure guided laser it is very easy there all simply monolithically deposited epitaxial layers one layer or another one layer on another whereas, to make such a structure you have to use several processes of etching and re growth it is called etch and re growth.

So, you 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 compare to the index guided lasers, for most of the commercial application it is sufficient to use index guided lasers which cost anywhere few dolor's, or few hundred rupees all the applications which they used for pointers and a various applications it is a gain guided lasers which is used. Because you can fabricate in bulk very large numbers and very simple processes of epitaxially depositing layers required layers 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 re growth with another material and that is a and these cost at least 10 to 100 times more than gain guided lasers. The cost of these or 10 to 100 times that of gain guided lasers, but when 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 waveguide the field profile is the profile of the mode of the waveguide 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 is equal to 10 mile ampere then you want to pass 50 mile 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 a field profile does not change because the field profile is determined by the optical waveguide. Lets the optical wave guidance which determines the field profile that is the transfers mode profile of the laser beam whereas, in the case of a gain guided laser see this now it will become clear.

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 it is here and here is the field which is generated in this direction it is guided it is a planar slab waveguide, but from the sides there is no confinement no confinement from the sides everywhere it is front view please remember have always I am discussing about the front view means is coming like this from the transfer side there is no confinement.

So, when I pass a current of i. I equal to let say 20 mile 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 mile ampere and assume that this much, I hope you are able to understand this is the transfers direction. This is I have shown is n of x let say n of 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 mile 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 with in this region there was gain within this x value now because my carrier concentration and passing more current which means the carrier spread is more and therefore, over a wider region we can expand this and you can expand this and you can see over a wider region there is gain which means this part size will become now bigger. You have 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 happened 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 will change. So, whenever you want an application where you want to maintain a constant field profile for example, you want to use it in holography where you have to record you do not want the field profile to change, but if you are focus is only on intensity.

Intensity of the laser beam if you want to make used you do not worry about the field profile spreading or not you just want to intensity there you increase the current you want more intensity, then if does not matter. So, most of the consumer lasers are these once 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 bier of laser diodes working in some company with there is always a specified index guided lasers to in the technical data sheet you will see index guided, or gain guided, index guided will be much more expansive and therefore, depending on unless your application requires index guided there is no point in buying index guided laser.

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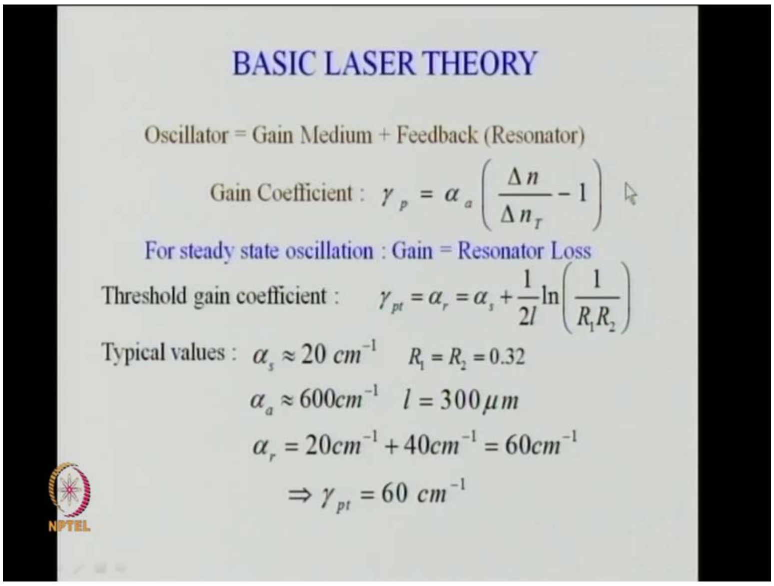

The basic laser theory, we briefly discussed yesterday its an oscillator laser is an oscillator which means it is gain plus feedback the gain coefficient peak gain coefficient is given by an expression of this form. So, if you are looking at the peak for the frequency corresponding to the peak gain, if we equate this gain coefficient to the resonator loss. So, that what written here for steady state oscillation, gain equal to resonator loss which means at threshold this is gamma p t the peak gain coefficient at threshold is given by equal to the resonator loss which is here and substitute some typical values. Yesterday we have done some numbers and you see gamma p t is 60 centimeter inverse yesterday I had taken probably the same numbers write typical numbers these are.

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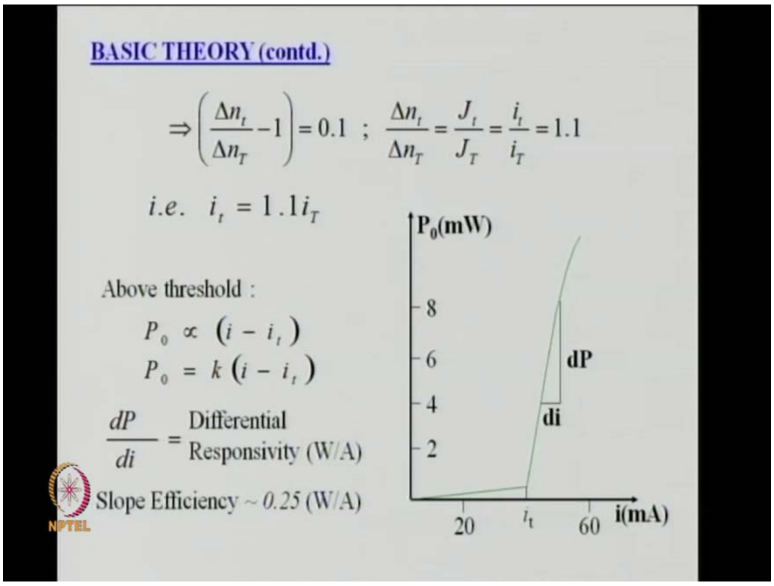

What we now bring the concept of threshold current. One is transparency current and the other is threshold current. So, both are here.

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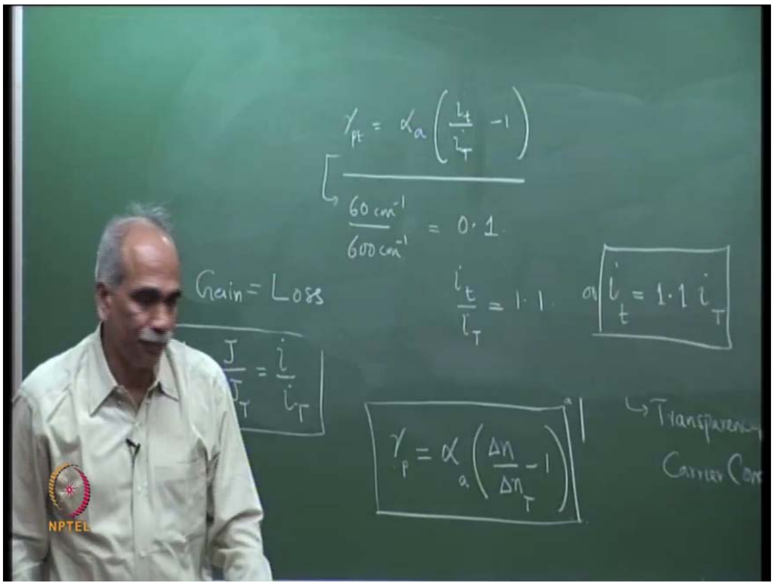

So, you equate gamma p t at threshold gamma p t is equal to alpha a into delta n by delta n T. So, this is delta n by delta n T minus 1 I can replace by this delta n by delta n T by i and i T transparency because I have shown here it is i/i T because in a practical device you pass current your control is on current. So, i by i T minus 1.

So, the threshold current how much is this threshold at threshold therefore, we make i T the small t standing for threshold. Capital T standing for transparency how big is this i T compare 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 the material loss coefficient. So, this is equal to 0.1 alpha a by gamma p T which means i T i threshold by i T minus 1 equal to 0.1 or minus 1 goes to the other side 1.1 or I threshold i T is equal to 1.1 times i T.

So, if you reach transparency current another 10 percent I had if you go then you will reach the threshold current please see transparency current you see the clear distinction between the two transparency current is the current when the medium is no more absorbing any current beyond that E 1 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 equal to loss. So, gamma p T equal to loss. This is clear and therefore, the threshold current is always more than transparency current, this is when gain starts this is when is equal to loss and therefore, the threshold current is little higher than transparency current.

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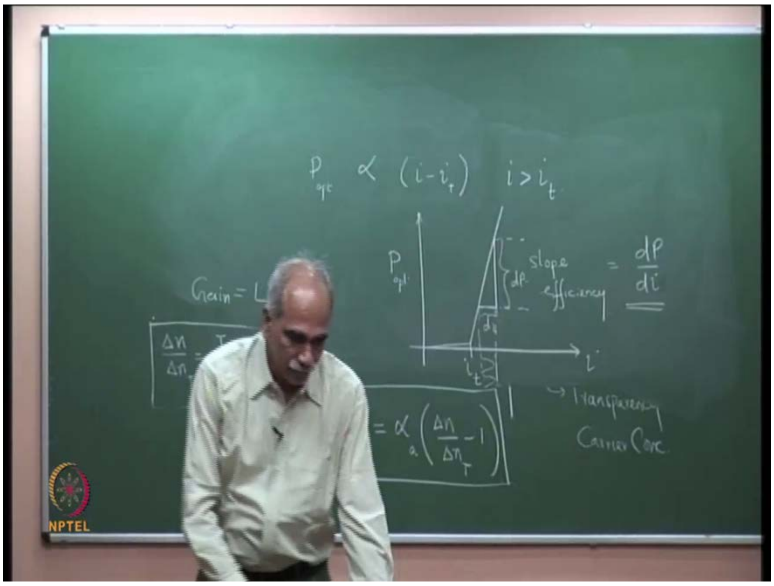

So, beyond the threshold beyond threshold, the power generator is proportional to the p optical is of the laser is proportional to this i minus i t which means. So, for i greater than I greater than i t because up to i t we need current to compensate for the losses in the resonator any additional current will give you additional optical power and therefore, p optical is proportional to i minus i T is the linear dependence and that is why you get the laser characteristic which is and here is the laser characteristic therefore, you have I and p optical when there is hardly any output up to the threshold this some output which comes because of spontaneous emission the laser is because of stimulated emission and here it is start.

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 mile amperes as a threshold current the laser diodes have 30 to 40 mile amperes. Normal once there are laser diodes which have threshold less than 1 mile ampere and there are laser diodes which have threshold much higher high current or high power laser diodes have threshold is higher normal once have about 20 to 40 mile ampere.

So, this is the current variation that is described in the one of the classes I had mentioned that the laser output is characterized by slope efficiency or differential response unity, slope efficiency which is the change in power d p for a change in current d i. So, d p/di is the slope efficiency this is equal to d p by d i is called slope efficiency. You would like to have has high as a slope efficiency as possible. So, that a very small modulating current here a very small excurtion in a modulation signal here will lead to a large excurtion in the optical power. So, the slope efficiencies important for modulation. So, typical numbers are given 0.25, 0.35 and. So, on it is also called differential responsivity output characteristic.

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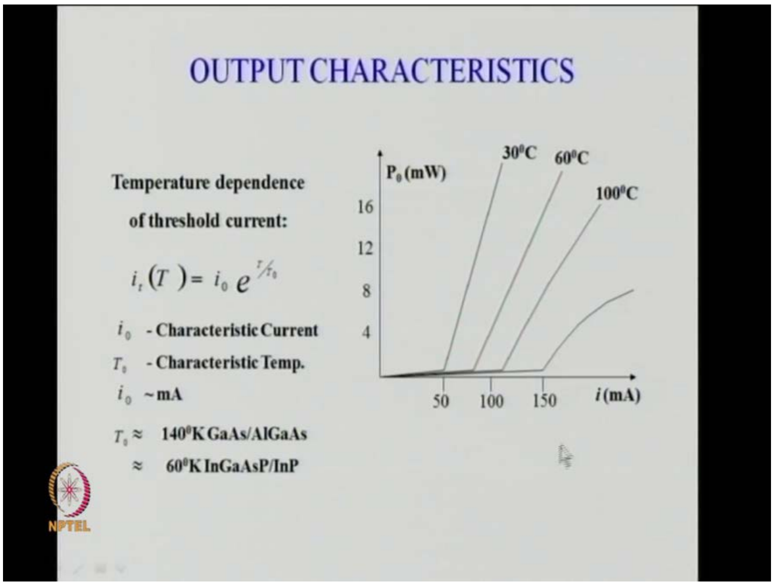

So, we come to the output characteristic earlier in the previous graph I had shown just one, but here what is shown is output characteristic with temperature and you can see that it is extremely sensitive to temperature the threshold which is here at the bottom. So, here is the threshold. So, at 30 degree if the threshold is 50 you see that at 60 degree it is increase to some 70 or 80 mile amperes. So, threshold is a strong function of temperature.

And therefore, what it means what is this simplification this simplification is if you had biased here let us say here at 75 mile ampere in this diagram at 75 mile ampere reverse biased which means at 75 mile ampere it was giving some power here optical power which is let say 10 mile watt 10 mile watt at 75 mile ampere at 30 degree centigrade due to some reason 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 mile ampere. So, you had bias heated 75, but the threshold becomes 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 paltrier cooling elements to maintain the temperature.

So, laser diode drivers you will see that will always have temperature controller you have to maintain constant temperature if you want to use a particular characteristic is very sensitive this characterized by. So, what is given by here is an expression above we can see that i T the threshold as a function the threshold as a function of temperature is i 0 into e to the power i by i naught T by T naught it is e to the power capital T by T naught T naught is call the characteristic temperature this is the material property.

So, you can see some values of T naught are given it is 140 k for gallium arsenate larger the value of T naught means less sensitivity is for temperature. In fact if you use quantum well lasers the T naught is very large for quantum well lasers they are much less sensitivity to temperature variations typically 350 375 degrees is the T not value for quantum well structures whereas, a indium phosphide lasers are more sensitive here you can see it is T naught is. So, this is the relation we tells 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 and tau drops rapidly means you see there is tau somewhere where is tau in the expression for delta n T.

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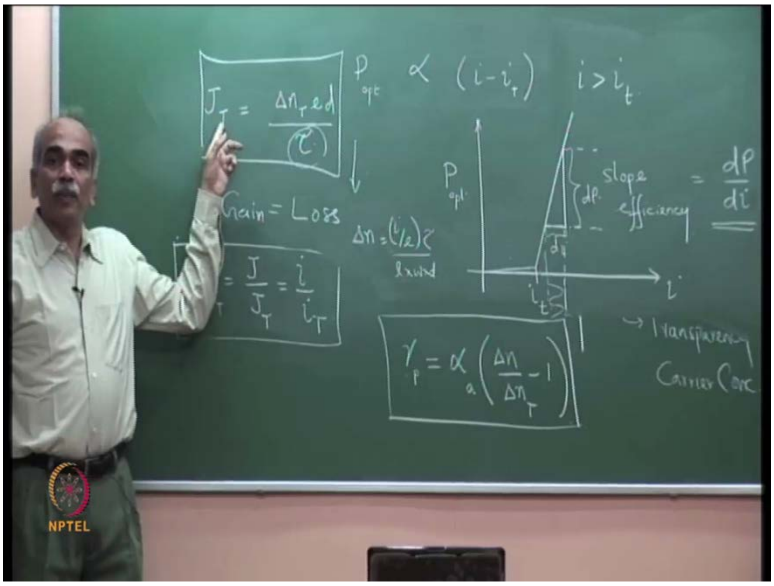

We have in the expression for J T the transparency current density drops down rapidly J T is equal to delta n T this is a parameter to get the required separation into. So, we had e into d divided by tau we had delta n is equal to alright delta n please see. W e had this expression delta n is equal to i by e into tau divided by l into w into d.

So, i by l w is J. So, j d and therefore, a J T is equal to. So, this is j into therefore, this tau drops down rapidly with temperature the recombination carrie, phonon transitions and if this drops down transparency goes up the transparency current density when therefore, the threshold will goes up.

So, i T goes up J T or i T goes up and threshold is about 10 percent or 20 percent more than the transparency and therefore, the threshold current will goes 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 a output characteristics, device characteristics various special profiles wavelength profile, spectrum and modes and so, on.