Fiber – Optic Communication Systems and Techniques
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Lecture - 38
Optical properties of semiconductors-II
(Gain, absorption, recombination rate) Homojunction lasers

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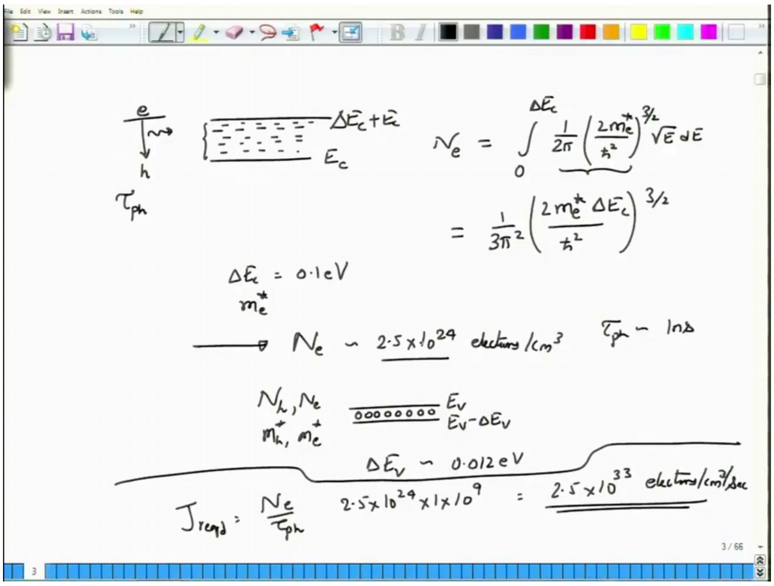

$$N_e = \int_0^{\Delta E_c} \frac{1}{2\pi}\underbrace{\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2}}\sqrt{E}\,dE$$

$$= \frac{1}{3\pi^2}\left(\frac{2m_e^*\Delta E_c}{\hbar^2}\right)^{3/2}$$

$\Delta E_c = 0.1eV$

m_e^*

$\longrightarrow N_e \sim \underline{2.5\times10^{24}}$ electrons/cm^3 $\tau_{ph} \sim 1ns$

N_h, N_e

m_h^*, m_e^*

$\Delta E_v \sim 0.012eV$

$J_{reqd} = \frac{N_e}{\tau_{ph}}$ $2.5\times10^{24}\times1\times10^9 = \underline{\underline{2.5\times10^{33}}}$ electrons/cm^3/sec

Hello and welcome to NPTEL MOOC on Fiber Optic Communication Systems and Techniques. In this module, we will continue our discussion of semiconductor optical properties of semiconductor and therefore see how lasers can be formed. So, at the end of the previous module, we had this particular calculation done ok, where we showed that. The required current density to maintain an electron you know amount or the electron density of 2.5 into 10 to the power 24 electrons per centimeter cube would be about 2.5 into 10 to the power 33 electrons per centimeter cube per second. This value is usually quite large. So, we do not really require about 10 to the power 24 order of magnitude 10 to the power 24 electrons per centimeter cube.

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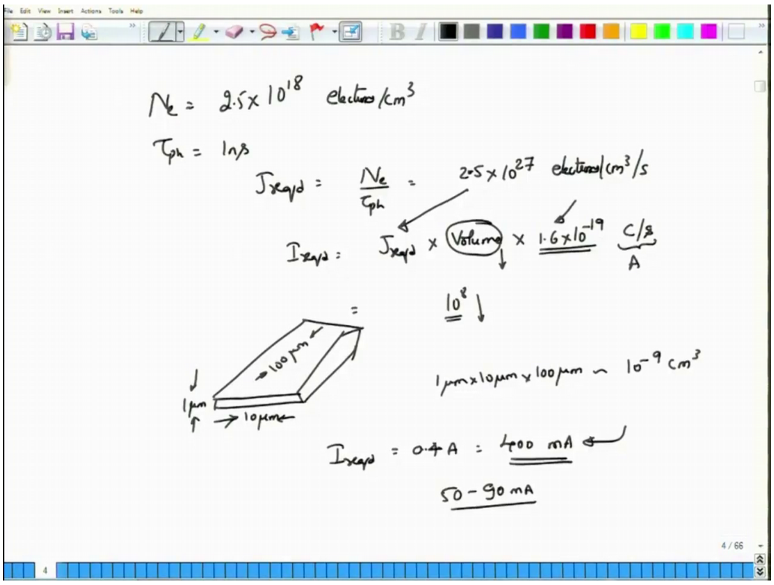

$N_e = 2.5 \times 10^{18}$ electrons/cm^3

$\tau_{ph} = 1\,ns$

$J_{reqd} = \frac{N_e}{\tau_{ph}} = 2.5 \times 10^{27}$ electrons/cm^3/s

$I_{reqd} = J_{reqd} \times \boxed{Volume} \times \underline{\underline{1.6 \times 10^{-19}}}\ \underbrace{C/s}_{A}$

$=$

$\underline{\underline{10^{8}}}$

$1\mu m \times 10\mu m \times 100\mu m \sim 10^{-9}\ cm^3$

$I_{reqd} = 0.4\,A = \underline{\underline{400\ mA}}$

$\underline{50 - 90\ mA}$

You require somewhere around 10 to the power 18, so let us say 2.5 into 10 to the power 18 electrons per centimeter cube is what you normally require, and of course the corresponding value of the holes as well ok. So, corresponding to this one assuming the photon lifetime is about 1 nanosecond, which is very typical for a direct band gap gallium arsenide material. Then the required current density would be N e by tau ph which turns out to be about 2.5 into 10 to the power 27 electrons per centimeter cube per second right. So, this is what you have.

Of course, this is still going to represent an extremely large amount of current, because the current would be multiplied by the required current density, and the volume over which you want this current density to be present, and the amount of charge per electron right, which is about 1.6 into 10 to the power minus 19 coulombs, so that you eventually get coulombs per second, which will actually be amperes ok. So, this is the required current that you need.

Of course, you put the value of J required, and then this one is also present that would correspondingly when you multiply the order of magnitude will be about 10 to the power 27 minus 19 is about 8 right, so 10 to the power 8 coulombs per second times volume must be provided. So, but this value is still quite large; and this value of current can be reduced, provided we actually reduce the volume. So, while J required is quite high, if you reduce the volume, you cannot really do anything to the electron value the electron charge here. But, if you can reduce the volume, then this number can be brought down to more manageable levels right.

So, typical volume would go something like this, the typical lasers will have about 1 micrometer or rather the thickness is about 1 micrometer, and this one will be about 10 micrometer. So, let me redraw it correctly. Typical laser volume is about thickness is about 1 micrometer, and the so this is one micrometer this is about 10 micrometer wide, and then you have a length of about 100 micrometer, so that the volume over which you are actually looking at a laser will be about 1 micrometer times 10 micrometer times about 100 micrometer, which turns out to be 10 to the power minus 9 centimeter cube ok.

So, when you now multiply this 10 to the power minus 9 into the volume case here or you substitute that into the volume case what you get, as the required current will be about 0.4 amps or 400 milli amperes. Now, this 400 milli amperes is quite manageable, most laser driver circuit will offer 400 milli ampere without any problem, some laser drivers also offer 1 amperes of current if you wish, and those are really the high power laser.

So, for most communication laser purposes 400 milli amperes, in fact this 400 milli amperes is according to an older technology, these numbers have been substantially reduced or these numbers will be substantially reduced, when you go to what is called as a quantum well laser or a double hetero structure lasers. So, the numbers of the required current to start of this process of lasing or the pumping current requirement is considerably brought down most modern DFB lasers require anywhere between 50 to 90 milli amperes to achieve lasing, which is tremendously small amount of current requirement ok.

So, the point to note here is that the current requirement of a semiconductor laser diode would depend on the photon lifetime, that is a lifetime of recombination from in the in the materials ok. When you when you have an electron combining with the hole by making a transition from the conduction band to the valence band, and it requires what is the amount of holes or electrons necessary to actually create a situation equivalent to population inversion. It is not really population inversion, because all you have doing is you have move the electrons from one band to another band right, it is not like what the you know earlier laser basic module covered. You first excite these electrons into another higher level, and then let them drop into an intermediate level, no nothing like that.

If you simply take a junction forward bias it, you inject electrons from the n side into the p side, you inject holes from the p type to the n side. And whenever this recombine electrons being injected here, and holes being reinjected here from one side. When they recombine, then they will start releasing the photons right. So, a simple current and forward biasing of the junction is sufficient to create lasers ok, I mean I am simplifying a lot, but this is basically what is happening at the big picture level.

And when they recombine, they emit light. Of course, that leads to an interesting question as to why does not my ordinary photo, I mean ordinary diode you know when I forward bias it in a circuit that I do in the lab, start emitting light. The simple reason is that those diodes are made out of silicon. And silicon is an indirect band gap material, and it will not lase as we have seen in the previous you know modules.

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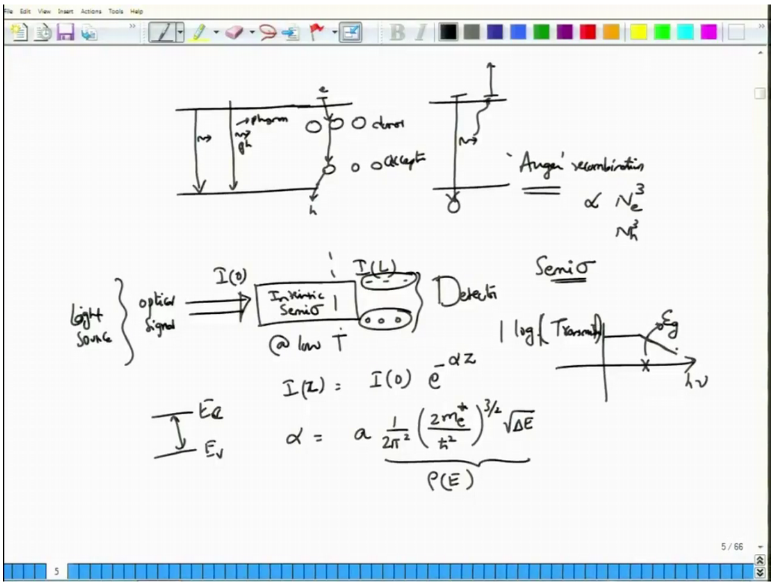

$$I(z) = I(0)\, e^{-\alpha z}$$

$$\alpha = a \underbrace{\frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2}\sqrt{\Delta E}}_{\rho(E)}$$

Of course, it is not just only this way that radiation can or you know radiation or recombination can occur, there are additional types of recombination, so one is of course, a direct band to band transition. Sometimes the band to band transition will have to be assisted with you know phonons. So, this is how the photons are there, and this is the phonons. So, this is phonon. So, this type of combination also emits a photon, but it also requires an assisted phonon, and this is still in the direct band gap case itself.

And you might have some acceptor levels or the donor levels sitting here, and these levels are the traps as we would call them and their temperature dependent ok. So, electrons can jump first to them, and then jump to another trapped state, and then finally jump back to the holes and recombine itself. So, this is one additional type of transition that may happen ok. But, you see that there are three processes involved, and therefore the probability of this one will be quite small. Nevertheless, when it happens, it will lead to degradation of the laser performance, and therefore this should be avoided. So, these are the donor states or these are the acceptor states, which are deep lying ok, and they contribute, these are the impurity traps that contribute to unwanted emissions.

Finally, or as a last example, you have an interesting transition. So, when there is a electron to hole recombination, it will emit a photon, but then this photon energy will be absorbed by an electron here, which will then move up into the state. So, it will actually take up the electrons in the conduction band, we will take up this emitted photon energy, and then move up in the energy level. So, this process is called as Auger recombination.

And the problem with this Auger recombination is that it is proportional to the cube of the carrier density, so it is proportional to N e or N h cube. And therefore, as the concentration increases, then this Auger recombination increases, thereby reducing the number of electrons are holes that are available for the recombination the fundamental recombination, which contributes to the lasing ok. So, it is one good thing to actually push lot of carriers into the conduction band and the holes ok, a holes into the valence band.

But, then when you do so, you are also increasing the chances of this Auger recombination, which is unwanted recombination for our purposes. So, these are all the different types of recombinations that may happen. But, in reality, we would not really be studying these recombinations in these details or to study this of course, would be a subject of its own, but it is also quite difficult subject of its own, therefore we would go into that details in this course.

But, what we want to understand is how to relate absorption and gain of a semiconductor material. And to do so, let us assume that we are working in with a intrinsic semiconductor, so here is my shorthand notation for a semiconductor, it is semi, sigma denotes for conductivity or conductor. Therefore, I am just using this notation, this is not the standard notation, I am just using it to avoid writing conductor everywhere. So, I have this intrinsic semiconductor. And this semiconductor is kept at very low temperature. I am not saying that this temperature has to be 0, in fact it should not be they have kept at low temperature, so that there is sparsely some electrons here, sparsely there are some holes in the valence band.

Now, suppose I send in external optical signal ok, so I will take signal from some other optical device, so this is another light source. So, this is light source, which sends out this optical signal. And what we want to know is to put a detector here, and measure what is the intensity of the light that comes out of the semiconductor, assuming that there are no losses in between or losses have been accounted for. What we are interested is to know what will happen to the intensity that you incident at this point to the intensity that you would be seeing at the output of the semiconductor or the other end of the semiconductor.

It turns out that this intensity of light actually decreases ok; it decreases as e to the power minus alpha z ok. If you are looking at you know at any point z along this semiconductor, it will decrease as e to the power minus alpha z ok. But, alpha here is actually given by some proportionality constant a divided by 1 by 2 pi square 2 m e star divided by h bar square to the power 3 by 2 square root of delta E; delta E is of course, the energy spread.

Why this particular component here, now what is this component? This of course is your energy or sorry this of course, is a density of state. So, what we mean here is that if there are certain electrons available, then these electrons will absorb part of the optical signal, and then thereby get excited into the conduction band right. And the availability of such electrons or then how much states are available for these electrons to absorb, and therefore go into the conduction band is governed by the density of state equation or the expression. And of course, it is also dependent on the intrinsic absorption property of the material, which manifest in the form of the complex permittivity of the material itself ok.

So, those details are not really important, but the id but the important point here is that as the optical radiation passes through the semiconducting material, it loses the photons or it loses its intensity, or its intensity decreases, because these electrons which are now present, they can start going into the you know conduction band by absorbing this amount of optical energy ok. So, at the output, you will see a exponential decay in the intensity of the light.

Now, if you plot this transmission ok, how much of the light is actually transmitted, what you will see is a very interesting thing. And not going to plot this transmission, I am going to plot the log of this transmission, so that the exponential will be gone, and then you will have a simple alpha z minus alpha z out there ok.

It turns out that if your radiation or if the optical signal has an energy below that of the band gap, and remember the band gap is the difference between the conduction and the valence band. And if this energy is or if they externally applied optical signal has an energy less than E g, which translates into a certain low frequency limit for this e g, then their transmission will be completely unity.

Meaning that no electrons or holes are absorbed, and whatever the magnitude of the transmission that I am plotting here right log of magnitude of the transmission would actually be completely 1, which are of course, I am accounting for all the other losses and throwing them away. Purely from the semiconductor perspective, there is not sufficient energy for the electrons in the valence band to absorb that and then move into the conduction band ok. So, the transmission will be almost equal to unity.

Whatever the electrons and holes that are present as a result of thermal energy will still absorb, and go you know become something else. But, as long as a energy is less than this energy gap, the transmission these events can be almost neglected to the transmission will be unity. But, I have the transmission or as the energy of the applied optical signal increases, the transmission starts to decrease ok. And this transmission starts to decrease simply, because now there is sufficient energy for the electrons in the valence band to absorb, and then move into the conduction band. So, this is about intrinsic semiconductor.

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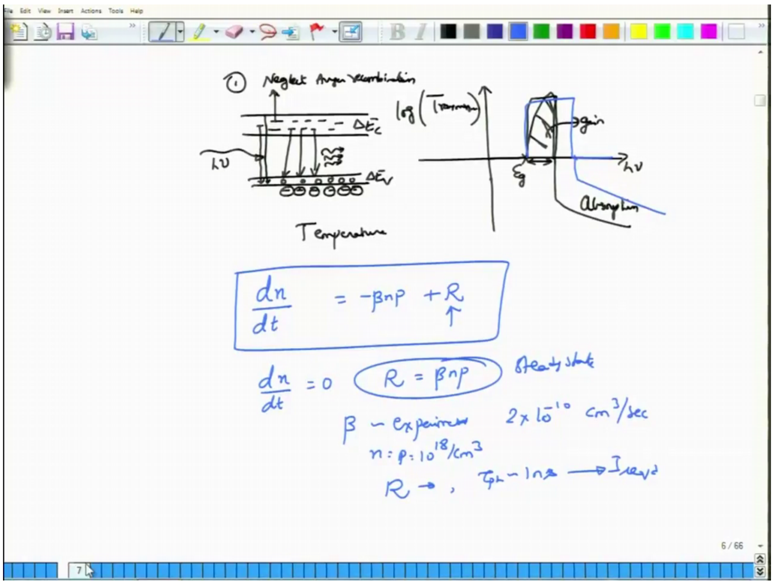

$$\boxed{\frac{dn}{dt} = -\beta np + \underset{\uparrow}{R}}$$

$$\frac{dn}{dt} = 0 \quad R = \beta np$$ Steady state

β ~ experiment 2×10^{-10} cm^3/sec

$n = p = 10^{18}/\text{cm}^3$

$R \rightarrow$, $\tau_{R} \sim 1\,\text{ns} \longrightarrow I_{\text{req'd}}$

What about a doped semiconductor or a semiconductor that is kept at a slightly higher energy level? So, by doping or by keeping the energy levels higher, what we would have created is we have created non-zero delta E c and non-zero delta E v that is we have created holes, and we have created sufficient electrons ok. And now, when you start sending in optical signal again, then what happens is that these electrons and holes can now talk to each other, and this can also be possible as we increase the temperature as well ok. So, higher temperature means now there is extra energy available, so that this energy can be absorbed by the electrons, and then moved into the conduction band ok.

So, as we increase these numbers, we increase the chances that radiation or chances that optical signals can be absorbed, and you know the carrier density can increase on the conduction and the valence band, which means that we actually start well actually there are two things (Refer Time: 15:17) going to happen right.

So, once as the energy comes in and if we have sufficiently if you have already created number of electrons in the conduction band and the holes in the valence band, the electrons which are there here, (Refer Time: 15:29) actually pushed down. So, these are the ion electrons which are not participating in the conduction, but as the holes are there.

But, now h nu the auger recombination can occur that is the electrons can actually absorb this energy, and then move into the higher energy state. And the valence electrons also can do the same thing, and then push this boundary of the valence holes below it. But, most importantly what you would actually see is that this assuming that the concentration is not too high, when we will neglect this process ok, we will neglect this auger recombination process.

What we are now seeing is that this light, so this is the first thing that could have happened. Now, what we have now seeing is that the light which is now incident ok, can stimulate electron to hole recombination right. So, it can stimulate an electron to hole recombination, thereby increasing the amount of photons that are available at appropriate energy levels.

From this is very important at appropriate energy levels, because this energy may be the one that is equal to this transition or it could actually equal to this transition right. So, you need to have an energy, which is greater than E g of course, but within this delta E c and delta E v plus E g right. So, if your optical signal is between that, then there is instead of absorption and loss of signal, what you actually see is a gain right. So, if you look at the transmission, what you will see is that initially there would not be any transmission, I mean this one until the energy reaches a minimum of E g.

And thereafter, you will actually see a gain and then drops out, and then becomes a absorption right. So, I am representing again log of transmission, but not the magnitude ok. I want to show the gain and the loss here. So, this is the gain term ok, and this is where the absorption is happening. And the width of this one is or the spread of this one is of course determined by delta E c and delta E v. So, this is the spread around which you will actually have the gain spectrum, but then you will also see that this gain spectrum can be moved or it can be increased depending on the change in the you know temperature.

So, as the temperature increases, then there will be significant increase or widening of this energy gap. And therefore, that can also be done. And this is the reason, why we actually say that even the gain spectrum can be expanded in frequency or the line width expands in frequency as the temperature increases ok.

Finally, the recombination rate equation that is important you know something that we had already written in the case of a rate equation for the simple lasers that we consider generic lasers that we considered. Here we need to modify them slightly there the rate equation actually corresponded to the reduction because of the spontaneous emission, and reduction because of the stimulated emission, after the given appropriate level appropriate energy level and so on.

Here, we do not really have that one, rather what we have is there is a recombination rate ok, which actually gives out the photons. And then there is a proportionality term, which is dependent on the population density of n and P. n stands for the electrons, and p stands for the holes. So, this is the recombination equation that we have for the case of semiconductors, you should contrast this equation with the generic laser equation that we have written earlier.

Of course, the given values of beta n and p, what values of n and p are required is set by the recombination rate. Alternatively, what would be the recombination rate is set by the values of n and p can be obtained by equating d n by d t to 0. And then you realize that R will be equal to beta n p in the steady state condition ok. So, given the carrier density and other things, you can find out what is R? Beta is an experimental quantity, so one of the values that it is normally found for gallium arsenide is about 2 into 10 to the power minus 10 centimeter cube per second ok.

So, if you want a population density in the order of 10 to the power 18, which would of course be the same for electrons and holes, there is 18 per centimeter cube. You can calculate, what would be the required R? And once you have calculated, what is the required R knowing that the photon lifetime is about 1 nanosecond, you can create or you can find out what is the required current, which I will leave it as an exercise to you ok.

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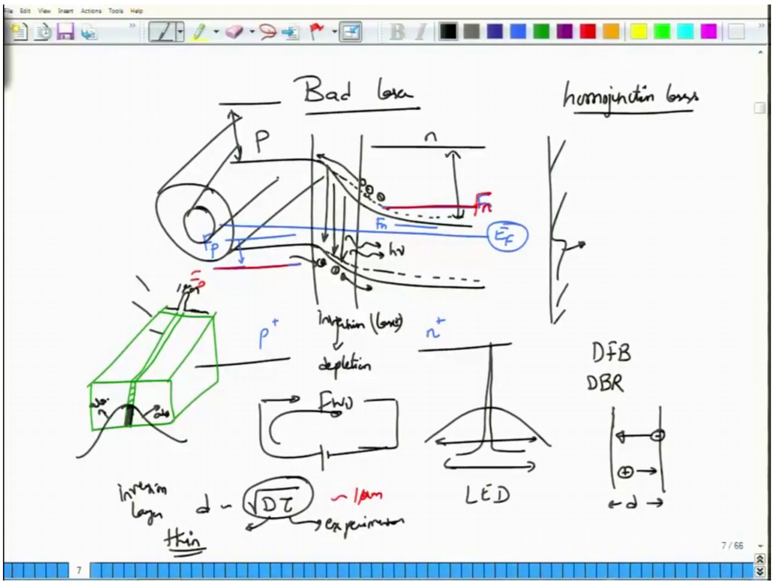

Now, before closing we will look at bad laser ok. Why do I need to look at a bad laser? Because bad lasers were the initial lasers that were fabricated, before people came up with novel ideas of improving the lasers. It is bad in the sense that it is possible to create a laser with this arrangement, but it will be very poor in performance, and it is highly uncontrollable ok.

The idea is very simple, you start off with a p n junction. So, you have a p junction, you have an n junction here. And this is a energy band diagram that you already know. Somewhere above will be the vacuum level, somewhere here will be the vacuum level, we have already talked about those vacuum levels ok, and this of course is the energy gap that you have right. So, this region in between is the so called depletion region what we normally call this one, because this is under the equilibrium condition. Under the equilibrium condition, you have the same Fermi level everywhere. It may not show it correctly, but this is how the Fermi levels are present.

But, when the p n junction is forward biased or it is reverse biased, the junction is not in equilibrium. When the junction is not in equilibrium, I cannot talk about a single Fermi level. Rather I should talk about what is called as the quasi Fermi level for the holes, and quasi Fermi level for the electrons. And you have to dope now in such a way that when you dope both sides heavily right some dope both sides with large amounts of holes and electron generating acceptors and donor atoms, so that this F p, which is an abstract quantity can be brought inside the p region the valence band. And this F n can be brought in this conduction band ok.

So, this is very important thing. For the lasers to actually have to form the lasers, it is not just sufficient for us to actually create just some amount of electrons, and some amount of holes in the conduction and the valence band. We have to dope them so heavily that the quasi Fermi levels for the holes and electrons actually fall into the band itself ok. Of course, in that case clearly the Fermi levels are not going to be aligned with in the non-equilibrium case.

And the other condition would be that that the value of you know the barrier height also reduces, because you have now started to forward bias the junction. So, when you forward bias the junction, you reduce the barrier height ok. And reducing the barrier height means, these electrons which are here can easily move or at least reasonably easily move to the p side region, and they diffuse while they do that. And the holes, which are present here will also be moved into this region. So, the holes also move into the region here. And when they are there, then they will recombine here to emit light and create a laser.

Of course this is just the emission part you have to actually support this semiconductor with the optical feedback. It is not done as by putting a mirror as it is shown, I will tell you couple of structures for feedback mechanism. How they are done, they are usually done in the form of what is called as DFB or DB are structures ok, where we embed a grating inside the material. And this grating kind of gives you the wavelength selectivity, because remember the spread of the line width emission cross section of a semiconductor is actually quite wide ok.

In fact, if you do not put in these mirrors, then you essentially operate under what is called as just the LED mode of operation, where the line width is quite wide ok. But when you put in a feedback structure, then it is possible for you to actually obtain high gain over a narrow spectral range, and that is what the DFB laser would make ok, where is the pumping here of course, the pumping is the forward bias voltage and the current supply that you have given. So, the current will move in this direction. And inject electrons from n to p holes from p to n, where they recombine and then give you the lasing output.

But, why do I call it as a bad laser? These lasers are called as homo junction lasers, because these materials on the p side and the n side are all the same material except that we have doped one side with larger p 1 side with larger N. From the manufacturing point of view, this is very simple. Because, fabrication point of view you do not have to worry about any additional material there is just a single substrate, which you grow and then one side you dope with p, one side you dope wit n, you forward bias, and everything should be all right.

Unfortunately it is bad, because the length over which an electron can move and the holes over which an electron or the holes will move into the layer, thereby causing the inversion layer. So, this is depletion layer for the electrical cases or the region for that one. But, this is the inversion layer for the laser application right, because there is abundance of electrons and abundance of holes, which can then recombine into this region. So, they were pushed and they recombine.

The length of this one unfortunately is very small, because it is governed by the diffusion and the lifetime of diffusion ok. So, this is the diffusion constant and this is the lifetime constant, which is usually measured experimentally ok. And this diffusion constant is determined by rather complicated calculations, which we do not want to go into.

But, the idea is that the length over which the inversion layer exist right is actually uncontrollable, because these quantities are usually not in our control their material properties, and they are also temperature dependent. So, it is uncontrollable, and it is actually very very thin ok. What is the implication of a thin thing? In fact, this layer will be approximately about 1 micrometer at most about 0.9 micrometer is typical, 1 micrometer is usual. And if you now look at the optical signal here, the optical signal or the optical mode would be coming in this direction.

So, if we actually look at a proper p n junction, this is how the junction would look like ok. So, this is the thin region over which you have created the inversion ok. And the optical signal would actually come out of this facet in this form or actually move into this facet in this form ok. It created at one phase and at the other phase it would actually come out in this way. Only this region is seeing the gain, and these tails are actually seeing lot of lot of absorption.

So, with the effect that the output region, what you would see at the output of the semiconductor, what you would see is a very highly developed gain region ok, which is quite small as well. But, almost no energy or no optical mode at this at the edges, because of this absorption of the band edges. And what is the problem with this one. When it when light comes out of such small aperture, which is about 1 micrometer, and then let us say you have a fiber whose cross section is about 4 microns or about 50 microns ok. Then what you are trying to have is a pinhole kind of an output, which is subjected to heavy diffraction ok.

As soon as the light comes out, it will spread out and then be expanded. And therefore, loses all of its coherence property, there most of its coherence properties. So, it would come out spread in this region, and therefore it will not be a good laser. To overcome these problems, I mean imposed by the homo junction lasers people in 1970 around 70 60 in mid 60 to 70 actually created or came up with what is called as a double hetero structure laser.

In hetero structure laser, the p side and the n side materials are still there, but there not of the same material ok. They are of slightly different materials, the base materials itself are different. So, one you have gallium arsenide, and then you have an aluminum gallium arsenide. These two are by themselves different. But, when you put them together, when you mesh them together in what is called as lattice matched growth, then they actually nicely mix amongst each other.

Therefore, they are known as miscible proper, I mean miscible materials. When they miss when they are miscible like nicely like that, then they can be easily grown one, one top of the other, and then they result in what is called as a hetero structure. Because, one of them will have a larger band gap, the other one will have a smaller band gap. And the implication of the smaller and the larger band gap is to actually modify the band structure, so that more electrons are accumulated, more holes are accumulated in the middle depletion region. Thereby increasing the chances of recombination and obtaining a very high gain ok. So, we will see this double hetero structure lasers, and that further final improvement of quantum well lasers very shortly, very briefly in the next module.

Thank you very much.