Semiconductor Optoelectronics
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Lecture - 21
The Semiconductor (Laser) Amplifier

In the last class, we saw the condition for amplification by stimulated emission. And today we will take it further and discuss about ‘Semiconductor Amplifier’. Have written ‘Laser’ in brackets, normally semiconductor amplifier here refers to semiconductor laser amplifier, but amplifier itself the device we will discuss in detail little later.

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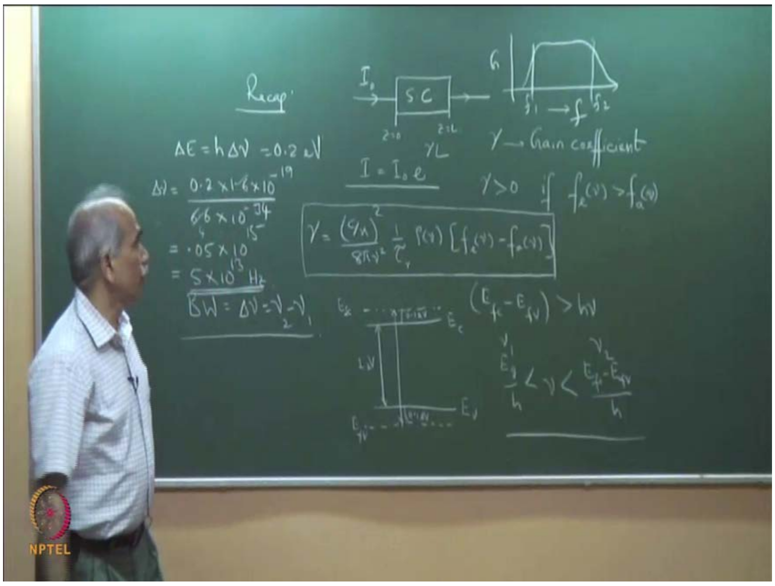

So recall, if you pass beam of radiation of intensity I 0 at the input of a semiconductor, then if I 0 is the intensity at z equal to 0, then at z equal to L, we have I is equal to I 0 into e to the power gamma L, where gamma is the gain coefficient is the gain coefficient. Gamma is greater than 0 or gain, if probability for emission is greater than probability of for absorption, probability of absorption.

The gain coefficient gamma is given by c by n whole square 8 pi nu square 1 over tau r rho of nu into f e of nu minus f a of nu. Rho nu here is the optical join density of states. We can substitute this here. So, gamma is greater than 0, if this is positive; if this is negative, then gamma is less than 0 and we will have absorption coefficient. And we will see the absorption spectrum a little later today.

So, this is the expression for gain coefficient. Today we want to know and we also have seen that, this is positive if E f c minus E f v is greater than h nu; for all frequencies for which E f c minus E f v is greater than h nu, we have gain or amplification. And from a simple band diagram here. So if, E c is here E v, then if E f c and E f v happens to be in the band E f c and E f v. Then for all frequencies which correspond to the range between this and this here, that is for frequency for which E g by h, less than nu, less than E f c minus E f v by h; we have amplification. There is amplification for all frequencies in this band.

So, this determines the amplification band width. So, if I call this frequency as nu 1 and this frequency as nu 2; then we know that the amplification bandwidth. So, bandwidth is equal to delta nu is equal to nu 2 minus nu 1. Typically, if this gap is save about 1.4 or 1.35, if you take a indium gallium arsenide phosphide amplifier or any amplifier if this E g is let us say 1 E v. And if I say that this separation here is just to get an idea 0.1 E v and this is also 0.1 E v; then what would be the bandwidth? Bandwidth will correspond to delta E and additional delta E of 0.2 E v.

So, delta E is equal to h into delta nu, is equal to 0.2 e V. The energy difference here corresponds to a frequency range and that is here, h into delta nu is equal to 0.2 E v. So, delta nu here, is equal to 0.2 e V; so I have convert it into Jules because h is in Jules; so 10 to the power of minus 19 divided by, 6.6 into 10 to the power of minus 34. So, you see how much this will be. So, this is approximately 4 times; approximately and this is 0.2 so 0.05. So, 0.05 into this is 10 power 15.

So, the bandwidth here is approximately 5 into 10 to the power of 13 hertz. In these semiconductor amplifiers have a bandwidth, which is of the order of 10 to the power of 13 hertz. What we have got is an expression for gain coefficient and an expression for bandwidth? What we would also like to know is the gain profile? How is the frequency response, if you take any amplifier normal electronic amplifiers, you would like to know the frequency response. You generally plot f versus gain and may be the amplifier has a gain curved like this; and you have the two cut of frequencies here f 1 and f 2 and delta f is this. The gain profile is also very important. There are applications where you need very flat gain profiles. So, we would like to see, what is the gain profile of this amplifier? So, we have got this number, cut off frequency, but we want to see the gain profile. So, let us see the gain profile. So, how to get the gain profile? We have to know the variation of gain with frequency; variation of gain with frequency.

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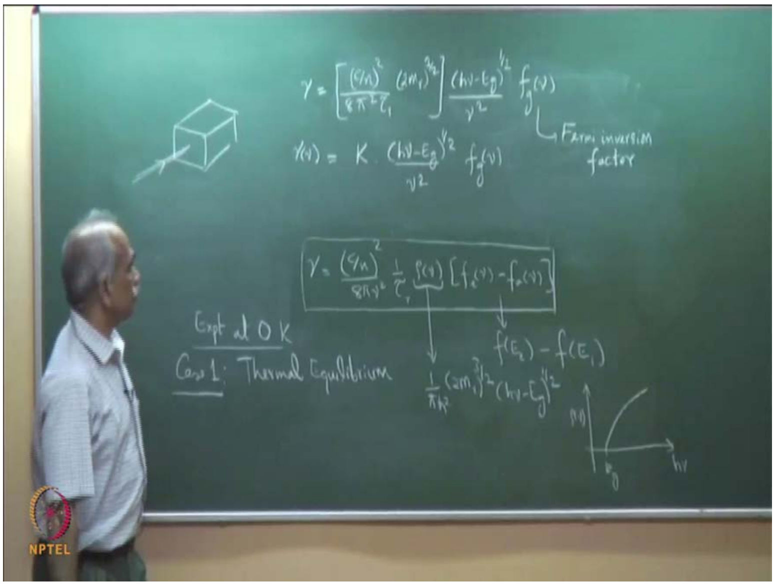

To begin with, we carry out a taught experiment; a taught experiment is this, an experiment at 0 K. Why we are using 0 K you can guess because there are Fermi functions here. f e of nu and f a of nu; f e of nu and f a of nu this is equal to f of E 2 minus f of E 1. You already substitutes you can substitute for the functions here and you get f of E 2 minus f of E 1. So, we want to perform this experiment here at 0 K. Now, at 0 K consider case 1; a semi conductor in thermal equilibrium. We know that there will be no gain, but let us see what we get? So thermal equilibrium, we have already seen that queasy Fermi levels. The separation between queasy Fermi levels have to be greater and we cannot achieve that at thermal equilibrium, but let us see what would we the profile.

So, what we now have is, we have a semi conductor. So, this is let say piece of semi conductor and incident radiation is passing though this. Let me rewrite this expression; gamma is equal to because I want to substitute for rho of nu. This is the optical join density of states; we have drive this expression 1 over pi h cross square, twice m r to the power 3 by 2 into h nu minus E g to the power half. Recall the density of states and we had a plot, if you remember h nu and from E g was going like this. Because, h nu minus E g to the power half is the variation. So, this is E g and this is rho of nu.

So, substitute this expression here. So, I have c by n square, 8 pi nu square; there is one come pi coming from here, so 8 pi square and h cross square. So, c by n divided by 8 pi h cross square; 8 pi h cross square. Nu square is there; I want to keep nu square outside, because I am interested in finding the frequency dependence of gamma. So, nu I do not want to get into this; so this, pi h cross. Oh no, let me write as it is let may not combined.

So, c by n whole square 8 pi square, 1 pi I have taken there; into tau r, radiative recombination life time; into 2 m r to the power 3 by 2, twice m r to the power 3 by 2; into this term is there. So, into h nu minus E g to the power half and there is a frequency dependence here nu square, this term nu square because this is independent of frequency this part. So, h nu minus E g to the power half by nu square, into this term that is f E of nu minus f a of nu. We denote it as f g of nu; where, this is called the Fermi inversion factor, Fermi inversion factor. Why? We will see why it is called inversion factor in a minute? So, this difference I am denoting as f g of nu. This is a constant gamma of nu here. So, r gamma of nu is equal to some constant K, some constant K into h nu minus E g, h nu this is nu; h nu minus E g to the power half by nu square into f g of nu. Let us look at the E-K diagram of the semiconductor.

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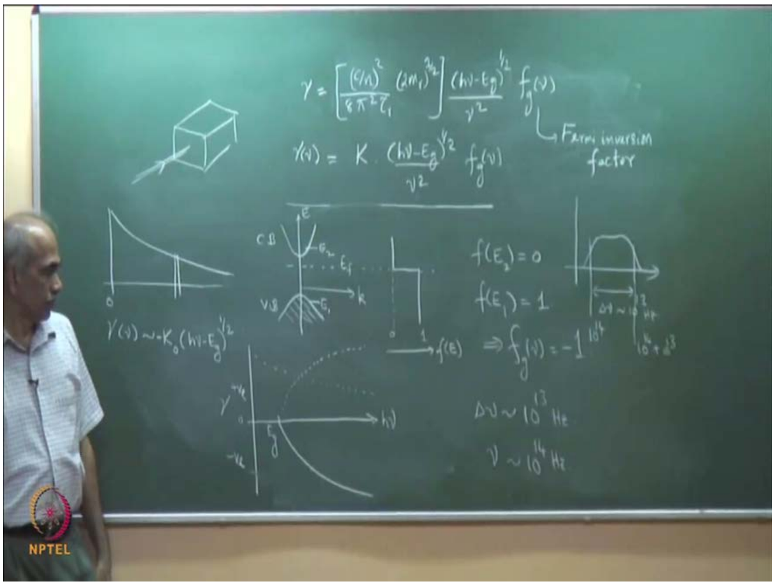

So, thermal equilibrium, a thought experiment at 0 K absolute 0. If we see the E-K diagram here, let say the Fermi level is somewhere here. I do not no somewhere there this is K, this is E-K; E f is somewhere here. At 0 K the Fermi distribution is given by a step function, so what I have now plotted here is 0, this is 1 and this is f of E. Which means, the conduction band is completely full; all levels glow the Fermi level are completely full. And the valen I am sorry, the valance band is completely full. So, this is valance band, this is conduction band and conduction band is completely empty. So, if you take any pair of states, any pair of states that is a value of energy E 2 here and the value of energy E 1 here. f of E 2 is equal to 0 and f of E 1 is equal to 1. Fermi function here base like a step function at 0 K. So, f of E 2 minus f of E n E 1, so at g what flew this implies f g of nu equal to minus 1. So, this factor is minus 1 at 0 K a semiconductor in thermal equilibrium. The Fermi function is somewhere here, you can take wherever you want the Fermi function; you can take a degenerate semiconductor also and see that you will get f g of nu equal to minus 1.

And therefore, the gain coefficient here gamma is equal to minus K into this. So, how would this look like. So, let us plot. Nu, what is nu? Nu is the frequency of radiation. We have seen that the typical bandwidth is delta nu, is of the order of 10 to the power of 13 hertz, 10 to the power of 13 hertz. And nu is of the order of 10 to the power of 14 hertz; the frequency 2 into 10 power 14, 3 into 10 to the power of 14, 4 into 10 to the power of 14; that is the kind of number that we have. Therefore, our interest is to find the amplification response. So, the bandwidth here, is approximately in our case delta nu is of the order of 10 to the power of 13 hertz.

So, in the range of interest here the frequency, the absolute frequency itself varies very little; that means, for example, you see this. This is 10 to the power of 14 hertz, means this end is 10 to the power of 14 plus 10 to the power of 13; a small number. If this is 1, this is 1.1. So, the variation of nu square over the interval, that is actually if I plot nu square that will have the variation; it is actually 1 by x square, please see it is 1 by x square. However, the range of interest, where x varies very little and therefore, I can either resume it as almost a constant; over the range of interest, this is 1 over nu square variation is almost constant. Because, 1 by x square. So, starting from 0, if you take 1 by x square; it drops like this, as you know; 1 by x square. However, we are considering a small range; this is if you take from 0, our frequencies are just 10 to the power of 14 plus minus 10 to the power of 13; which means, we are looking at a small variation here. Therefore, 1 by nu square varies very little and therefore, the variation is primarily determined by this.

So, at 0 K we have gamma of nu is equal to a constant K 0 into, f g of nu is minus 1; so minus K 0 into h nu minus E g to the power half. Pease see that 1 over nu square dependence is very small because our range of interest is very small. If you wish you can keep and plot, then also it does not make much difference. This starts from E g, this is h nu and plotting the gain coefficient gamma. f g; let me plot because it is negative, I need to plot negative as say. So, it starts from here, E g and this would h nu minus E g to the power half, would vary like this; therefore, minus h nu minus E g to the power half would vary like this. This is gamma, this is gamma is 0, gamma positive, gamma negative. We already know this that at thermal equilibrium gamma is negative, because f g of nu is minus 1. I want to keep this graph here and let us see now, let us go on to queasy equilibrium.

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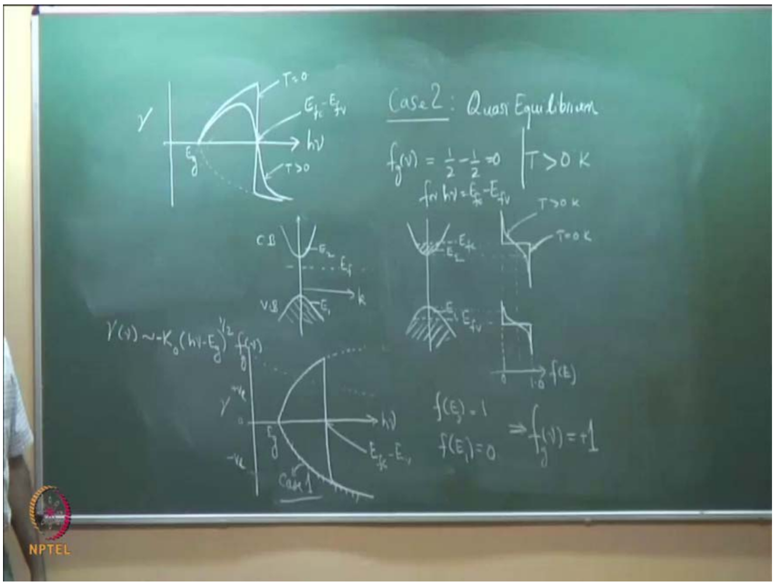

So, case two queasy equilibrium; case two, queasy equilibrium. The same E K diagram let me draw in parallel, but now we have pumped this semiconductor and assume that E f c is already in the band; E f c and E f v. Because we know that, we get gain only if the difference if greater than h nu; therefore, E f c is here and E f v is here. What does this mean? E f c therefore, the variation here would be and the variation here would be. So, on this axis I have plotted f of E. This is 1, 1.0; this end is 0. Corresponding to 2 Fermi functions, which described the occupation probability of the two bands at 0 K, the valance band is completely full up to E f v and the conduction band is full up to E f c;

therefore, if you now consider a level E 2 here and a level E 1 here. Note that f of E 2 is equal to 1 and f of E 1 equal to 0 implies f g of nu equal to plus 1.

So, you see the Fermi factor as been inverted earlier, it was minus 1 at equilibrium, thermal equilibrium and in queasy equilibrium f g of nu is plus 1. So, what do we expect the gain profile to be now? This one. So, the gain now in this case, again goes up like this. How far will it go? This is h nu the photon energy. So, let me just for differentiation let me show this like this. So, this is for case one, this is case one. How far will it go? h nu is the photon energy increasing from E g, it is increasing from this gap, this gap is E g it is increasing. When it is comes to E f c and E f v are beyond this. This is 0 and this is 1. So, the factor is inverted at E f c minus E f v. So, along this line at E f c minus E f v at the point, E f c minus E f v, the factor suddenly becomes from plus 1 to minus 1. When energy h nu comes here, that is becomes more then this difference; when it is comes here, then this is 0, this is one. And therefore, the factor in reverse and therefore, the gain profile drops down like this and continues on this line.

So, let me redraw this here. So, h nu beyond E g, it starts increasing as h nu minus E g to the power half drops down; this and continues here. So, this value here is E g and this value is E f c minus E f v. What is this on the axis, is gain profile gamma, so gamma versus h nu. So, this is the frequency band, in which amplification takes place and the gain profile looks like this. This is at T equal to 0. What will happen for T greater than 0 normal temperature? First thing you see is the Fermi function gets mired, so the Fermi function does this. So, it 0.5 it as to cross at 0.5, this is the Fermi function; this is for T equal to 0 K and this is T greater than 0 K.

This also is mires, so we have this variation; whatever be the temperature at E f c and at E f v the probability is half, so it is 0.5 here and 0.5 here. Which means; f of E f c minus f of E f v is half minus half that is 0. So, f g of nu equal to half minus half equal to 0, for h nu equal to E f c minus E f v. f g equal to 0; that f g equal to 0 means what, there is the gain expression so it was multiplied by f g of nu here, f g of nu. f g of nu equal to 0 implies gain equal to 0; and therefore, first point is at E f c minus E f v gain is 0 even for T greater than 0; the gain is 0 here.

Second if I take a frequency closed to this; that is closed to E g which means closed to the band gap here, you see f of E 2 is here have actually shown like this. But in practice as you know that, this marring is very little or f of E f c is close to 1, but less than 1. It is close to 1, but less than 1 and f of E f v here, that is if I take at E g; so please see this. h nu corresponds to E g, h nu corresponds to E g means E 2 is here; so the corresponding f of E 1 f of E 2 is closed to 1, but less than 1. Corresponding to E 1 here, f of E 1 is closed to 0, but greater than 0. So, just if I say that if this is 0.99 and this is 0.01, the difference is 0.098. As you increase this becomes smaller and this becomes lesser and lesser, it is it is going towards 0.5 and this is also going towards 0.5. Therefore, the difference drops down from 0.1 to 0.0. 0.1 to 0. Which means here near E g it is it is almost the same, but the difference increases and finally, here it comes down to 0. Let me draw this and then you this is for T equal to 0, this is for T greater than 0.

The difference near E g, the Fermi inversion factor f g is close to 1, but less than 1 and therefore, the multiplying factor is slightly less than 1. So, you see it starts, but as h nu increases, the multiplying factor becomes smaller and smaller and therefore, the difference between T equal to 0 and T equal to T greater than 0 changes. And we know that whatever be the temperature, the 0 crossing is this. So, if you actually put the numbers and see that you will get a gain curve which is by the same. This is the gain profile. So, if I want to independently plot the gain profile.

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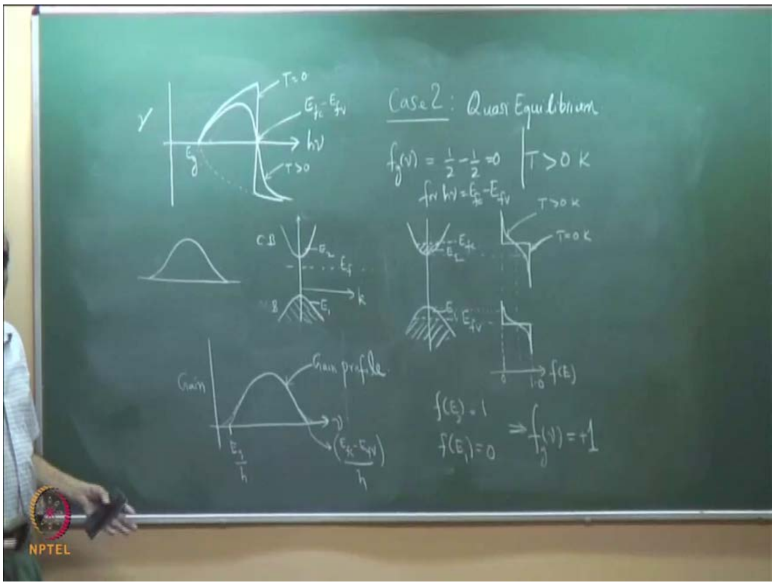

Then so if I plot gain, then you will have the gain taking a shape something like this; so this is nu. Let say at room temperature, T greater than 0. This value here is if this frequency, like you typically plot the frequency response; then this value here is E g by h and this value here is E f c minus E f v by h. I have not shown beyond that because beyond this it is negative, I am just plotting the gain profile. And typical bandwidth is 10 to the power of 13 hertz; these are practical numbers of semiconductor optical amplifiers. In theory it looks as if the gain starts write at E g and at E f c by is as if use its starting here and it is like 0, but in practice it is slightly different. The shape is the same, but the ends are slightly different; because of band tails states, these are highly doped semiconductors and therefore, there are band tails states and this tapers down in practice; like this and similarly it tapers to the same.

It is not an abreact band, this tapers down here and it looks like; it is not flat. The first thing that you see that semiconductor amplifiers, semiconductor optical amplifiers; do not have a flat gain, gain profile. And this is one of the reasons why in all WDM communications we do not use semiconductor amplifiers, but we use erbium doped fiber amplifiers; which have a flat gain profile. But the bandwidth in this case is quite large.

So, we know why this shape of gain profile that we have. So, the summary is that if you pump a semiconductor and maintain the difference between the Quasi Fermi levels greater than the frequency h nu at which you need gain, then it is possible to have gain. How do we pump the semiconductor? How to maintain this? The next question could obviously, how to how to have E f c minus E f v greater than E g? Is not going to be easy. We can have Quasi Fermi levels all p n diodes when you forward bias you have Quasi Fermi levels, but you are asking for too much; that is E f c minus E f v greater than E g.

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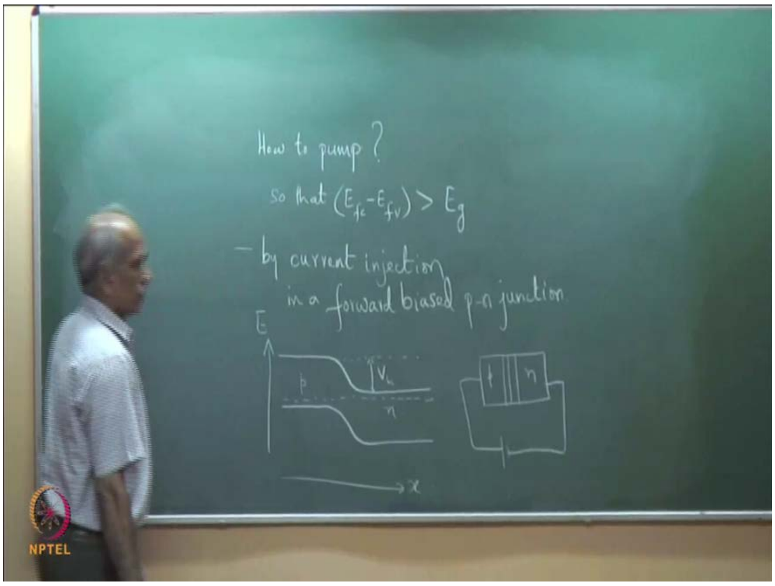

How to pump?

so that $(E_{fc} - E_{fv}) > E_g$

– by current injection in a forward biased p-n junction

So, how to pump? Any amplifier requires a pump, how to pump? So, that the question is incomplete there; how to pump? So, that E f c minus E f v is greater than E g. Greater than h nu for the frequency nu, but minimum is E g therefore, have written how to make it greater than E g. The easiest way is by current injection; the answer, I am writing the answer the first then we will discuss. By the current injection in a forward biased, forward biased p-n junction, forward biased p-n junction. So, what do we mean by this? So, you take a p-n junction, we have already drawn the band diagram. So, I will directly draw the band diagram. So, what we have is this the p side, this is the n side and we have Fermi level here; this is axis energy, this is the distance x before pumping. And there is a built in voltage, built in potential, so this is V built in; E into v built in is the energy. So when you forward bias the diode in our basic elementary picture, so we have forward bias. So this is p, this is n originally there was a depletion layer here and you forward bias. I can also plot the carrier profile across the junction, very quick recall of the basics that we have already studied.

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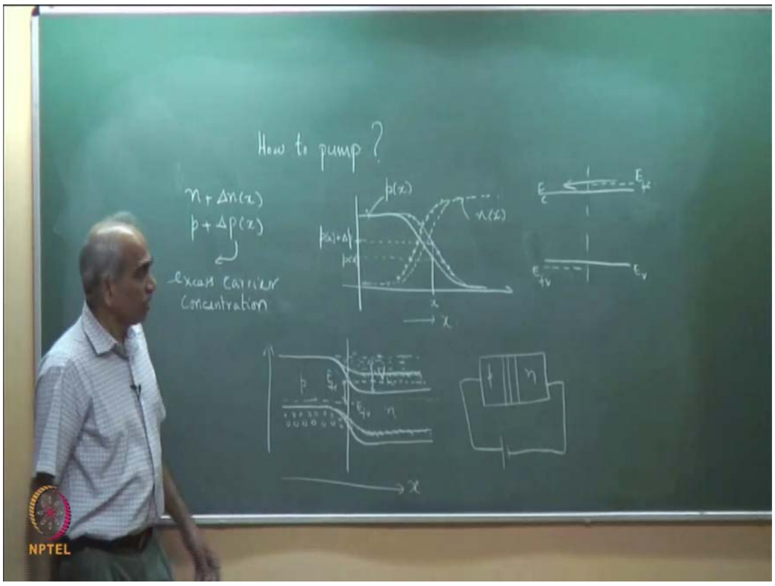

So, if you plot the carrier concentration. So, this is p and this is n; so p comma n. What I plotted? Is whole concentration p and this is n; and this is the same x across the junction. So, on this side there are very little electron, this is not a Fermi level. This is the concentration n of x. So, what I plotted is n of x and p of x, across the junction. On the p side you have large number of holes and on the n side you have, what happens when you pump? When you pump forward bias this goes up, you already discussed that. This goes up, which means the band now comes let say here and this band here. This is the new position; let me draw them with solid line itself and differentiate by putting crosses because so let me drawing this fashion. Just to differentiate the second case that is the after forward biasing, the Fermi level has to separate out because the Fermi level as to remain. So, the Fermi level this one is here and the next one has moved. So, E f c and E f v; so what will have this E f v and E f c. So, Fermi levels have separated out; good.

You pump harder, this will go further up; how much will it go? When you pump harder, please see this is full of electrons here, electrons are coming here. So, when you forward bias, the carrier profile now becomes like this. So, far away from the junction there is very little change, very little change; but at the junction now the carrier profile has changed. Please see this was before biasing, how do I show? Ok, let me put dots; just to differentiate this is after forward biasing.

And p profile has also moved like this. So, this is after forward biasing. So, what has happened is, at a given value of x; you see that both n of x and p of x have increased. There is what you see here, for if I had taken this value of x here, then earlier the number of electrons here was much less, but now we have large number of electrons. Similarly holes which were here have also moved to this side now, and that is why this is also moved to that is side. This was n of x please see, at any value of x if I take this as the x then this value here is p of x. After forward biasing this is this is p of x, after forward biasing this is the nu p of x; which means this value now represents p of x, p of x plus delta p of x.

Similarly you have n of x and delta n of x, the delta n of x we are looking at the junction region; please remember we are looking at the junction region because the changes occur in the junction region because of forward biasing. Delta n of x and delta p of x we have got in the junction region delta n of x and delta p of x, originally it was just n before forward biasing now it is this. This delta n of x and delta p of x are called excess carrier concentration. So, this is excess carrier concentration, excess carrier concentration. n and p where called carrier concentration, the delta n of x and delta p of x is called excess carrier concentration. And the point that we see is the Fermi levels as separate out.

If you pump harder the level goes further up at best, at best the two levels let us say got equal. This I have lifted this, the two levels have become equal. This is the p-n junction, original junction; now the level has been raised. Where is the Fermi function for this? It is here; where is the Fermi function for this? Far away from the junction please see this. This is the Fermi function of the p side. This was the Fermi function of the n side. So, it is still less than E c, there is this is now E f c, this is now E f v. Therefore, and this is E c and this is E v. What do you see? E f c minus E f v is still less than E g. This is I said this is at best, why I am saying this is at best? By the time you forward bias it is so much, the current through the device is so high, that the junction will burn up by this time.

There is no barrier, any electron injected here is simply going through the device. This is very, very high forward biasing and the junction will simply burn up. At you have not is the condition E f c minus E f v greater than E g. So, how to achieve this condition E f c minus E f v greater than E g? Can be think of something, yes. One of the ways is, we start with highly doped p and n, so that degenerate p side and degenerate n side. If we start with the degenerate p semiconductor, which means E f, c E f is already inside here and E f is already into the conduction band; in that case I can have E f sitting here and E y E f v sitting there. Please see, if I start with a degenerate semiconductor; there is a possibility of making E f c minus E f v greater than, so E f c E f v minus E f c greater than h nu.

So, first point is we have to use, it is necessary to use highly doped p and n materials to realize a p-n junction for a source, which can act as an amplifier. Even this is not a very practical solution; it is All right, it in it in theory it is possible; but as I said to achieve this kind of forward bias means, the current through the device is so high, that it will damage the junction. And it more practical and correct way of getting this is by the use of double hetero structures and which plotting as I said noble prize for that discovery, so use of double hetero structures. That is why it we discussed double hetero structures in details and trying to draw the band diagram of double hetero structures. Yes the method is by current injection, but in double hetero junction, double hetero structures; p-n junctions which form double hetero junctions. So, we recall the band diagram very quickly and now you see what happens? That leads to carrier confinement and the separation between E g and E f c and E f v can be easily greater than E g. So, recall the technique that we have for drawing the energy band diagram.

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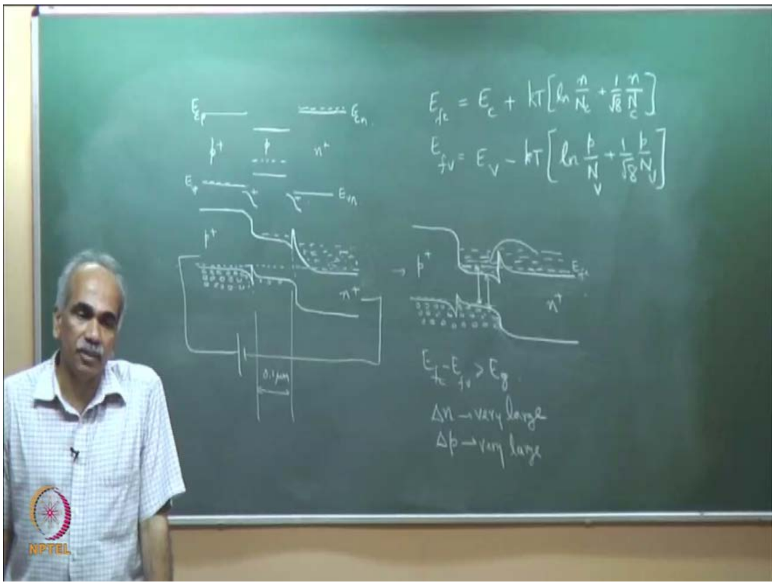

So, we have a double a hetero structure, with a low band gap material sandwiched between two high band gap materials. Highly doped p structure; so let me draw the p here or inside or inside the band. Let me for simplicity let me draw it; that is All right. And then we have another structure here, which could be slightly p doped or n doped or in drain sic and I take here highly doped n side here. So, this is n, n plus, this is p, this is p plus. This could be a aluminum gallium arsenate, gallium arsenate and aluminum gallium arsenate.

So, we join the; let us take the band diagram. So, one of the as I said you could start a anyway. So, let me take the middle one here and show the Fermi energy here and then we know that before forward biasing, the Fermi energy should remain constant. And it is p to the p plus therefore, the band will start bending like this here. So, the band, so let us the band will bend here and then there is a discontinuity, Fermi function is here. Therefore E; this is E c, E c of the p side; this is E c of the n side, E v of the p side and E v of the n side.

So, very quickly the band starts bending like this. Then it needs a discontinuity. So, I have a discontinuity and then the band continues, so the band continues. When it reaches this junction, this is a p-n junction. So, the band has to; so here also we have plus a potential energy variation like this, here also we have a potential energy variation like this. So, the band starts bending further, but it needs an upward discontinuity. So, we take this up. This discontinuity here and then this continues further and because finally the Fermi level has to be here.

Similarly this end, there is this end starts from here comes starts bending, but there is upward discontinuity here. So, this bends upward and then continues on this, comes here; this has an upward discontinuity, the downward discontinuity sorry. So, here there is a downward discontinuity, is discontinuity; downward discontinuity and then we have the band continuity. I show a little actually the angle should be more because it is n plus; so rapid drop. This is advantage of chock and board; I can wipe whatever mistake I make.

So, this is the structure, recall that this is there are plenty of electrons here; because this is a degenerate n semiconductor. Plenty of holes here and just I have to draw one diagram of forward biasing and then we will stop. More of discussions we will do later. Is the diagram alright? Clear. So, this is the p side p plus, this is the n plus side. We have not forward bias debt, we are forwarding biasing now.

So, we applied positive voltage to this side and negative to this side. As usual this will starts going up. So, this starts going up, so let me draw the diagram separately here; rather than showing in there; now very quickly. So this discontinuity; when we have this, when we have this and then I am now showing the forward biased. So, originally I had this here, similarly from here I have this; an upward discontinuity continuing like this and then from here there is a downward discontinuity and let me show like this. When I forward bias, this end is erased; and therefore, we have the new diagram which is coming. So, everywhere this portion gets raised here and this comes here. So, originally it was here, now this has come to this; and therefore the Fermi level here. Fermi level was inside the band, to the Fermi level is in; so E f c.

Do not worry, you do, you just have to see. I have raise this and therefore, E f c is here; E f v was here. So, E f v, so this also came up now, this got raised, this got raised and discontinuous; because the band gap has to remain the same, and this was here. The layer which is here, that is the sandwiched layer is off thickness approximately 0.1 micro meter. It is smaller than the junction width in normal p-n junctions and you have electrons, because of forward biasing electrons completely filling here. Because this has been raised and because this level went up, you have holes after forward biasing; what has happened? Look at the junction rejoin here, this was the p plus region and this is the n plus region. This is the junction region; in the junction region, E f c is already here. Why E f c is here? Because, the number of electrons are so large, that the Fermi functions has moved here into the band; and number of holes are so large, that here the Fermi function has come into the band. Now this difference you see, this is the difference which is larger than E g of the sandwiched layer. The difference between E f c and E f v is larger than E g of this layer, the layer which was sandwiched; the low band gap material.

Second point; first: therefore, you can clearly see that E f c minus E f v can be greater than E g. Second point: the carriers, the number of carriers here; number of carriers in a small volume is so large. That the excess carrier concentration delta n and delta p become very large. We will put some numbers and quantifies this, what is this very large, become extremely large. Because these numbers become very large, you know that; you recall, E f c and E f v by Joyce-Dixon approximation, you reads you recall this. E f v is equal to E v minus k T into l n, p divided by N v plus 1 over square root of 8 into p divided by N v. This is the Joyce-Dixon formula in which we have discussed earlier. The empirical formula l n, n divided by N c plus square root of 1 over 8 into n divided by N c. The carrier concentration n and p have become very large, because of the pumping excess can this p, is the original p plus delta p, delta p is due to current; current injection.

So, these p have becomes very large, p and n. And therefore, E f c and E f v, E f c becomes greater than E c and E f v becomes less than this. Because this is now a larger number, the positive number and you can clearly see that E f c minus E f v becomes greater than E g. So, E f c minus E f v becomes greater than E c minus E v, because both the quantizes here are positive large quantities. If this small n is less than N c, then this part will become negative, log of negative fraction. But now, when n has become very large, it becomes positive. We will put some numbers or you will put some numbers and see, but this is why double hetero structures are used in a laser devises. To achieve E f c minus E f v greater than E g, in a practical way by passing very small currents; as we put a numbers, we will see just by passing a milliamps; we do not have to pass hundreds of milliamps through the p-n junctions are fear of burning the junction. So, we will stop here and continue in the next class.