Microelectronics: Devices to Circuits
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Lecture No 03
BIPOLAR JUNCTION TRANSISTER: MODES OF OPERATION-II.

Hello everybody and welcome to the NPTEL online certification course on Microelectronics: Devices and Circuits. What we will start today's lecture by just recapitulating what we did in the previous turn. We had seen that given a NPN transistor where emitter is basically an N type, base is P type and collector is again N type, base width is very-very small, emitter doping concentration is the highest, base doping concentration is the lowest, and collector is moderately doped.

We have also seen the reason why the base is relatively lower doped. And the reason was that with low doping we will have less number of majority carriers there and therefore the electron-hole pair recombination there will be smaller. And as a result most of the electrons which started from the emitter side will reach towards the collector side and we will get large current on the collector side. So that was the prime reason why the base width was effectively very thin not only that the base doping concentration was also very small.

With these two things in mind we have also seen yesterday in the previous discussion or in the previous lecture that the base current itself consists of two components. The first component is primarily the current which is the base current which is coming out because of recombination of holes. So when electrons recombine with holes to replenish those holes you have to insert a current that is one part of the current, which is basically a current which is being supplied by the forward bias base to emitter junction.

There is also a current which is basically a current which is primarily due to the diffusion of the minority current carriers in this case electrons from hole to the from base side to the emitter side because that is though it is forward biased but for that it can easily move through the region. Now we have also seen in the previous turn that with this basic concept there are two types of transistors available one is known as NPN and we have also a PNP transistor. We have also seen the various modes of operation and how various modes of operation work under what condition. For amplification purposes we have learned your emitter base junction should always be forward biased, and your base collector should be reversed biased.

Similarly if you want to do in a cut-off mode then both junction's emitter base and collector base should be reversed biased. If you want to move into saturation then emitter base should be emitter base forward biased and base collector should also be forward biased and so on and so forth. So we did have two biases and two types of combinations so they were effectively four modes of operations of BJT which we have dealt in the previous turn.

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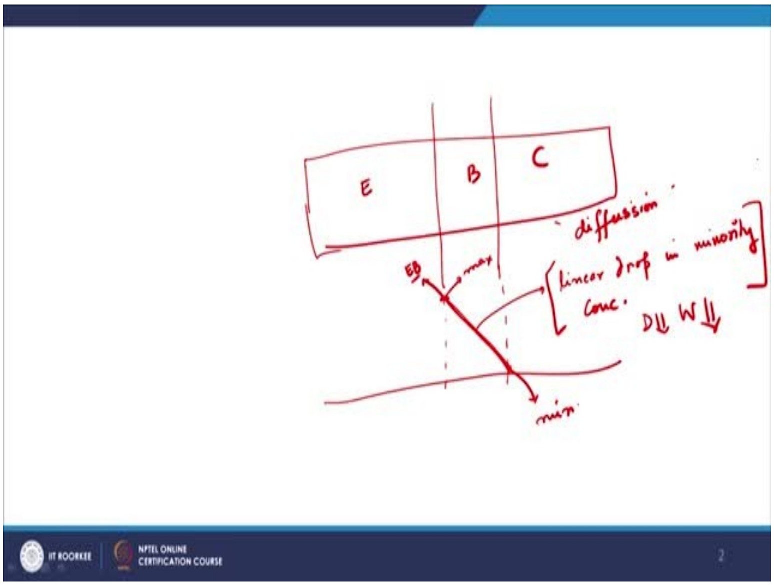

We have also seen that in the previous turn that if you have a therefore NPN transistor right. And then if you want to plot the minority current carrier concentration in the base region then it was shown to you that in the base region if I plot a graph then in the base region I would expect to see the minority current carrier concentration to fall almost linearly right. And this linear falling is primarily due to so this is basically a linear drop in minority concentration, right and this is minority concentration.

This is primarily to do with a thought that your doping was low and your width of the depletion region is also low. Under these two criteria we saw that it is almost like a straight line which is just falling between point. And as you can see so this is the emitter base collector this is basically your EB junction emitter base junction your concentration of minority current carriers maximum here right. And it becomes linearly to become almost minimum at this point we have seen why this profiling is being maintained to a larger extent. As you can see this will be primarily a diffusion phenomena right and therefore we will depend upon the concentration gradient of the charge particles which is basically here electrons within the base region.

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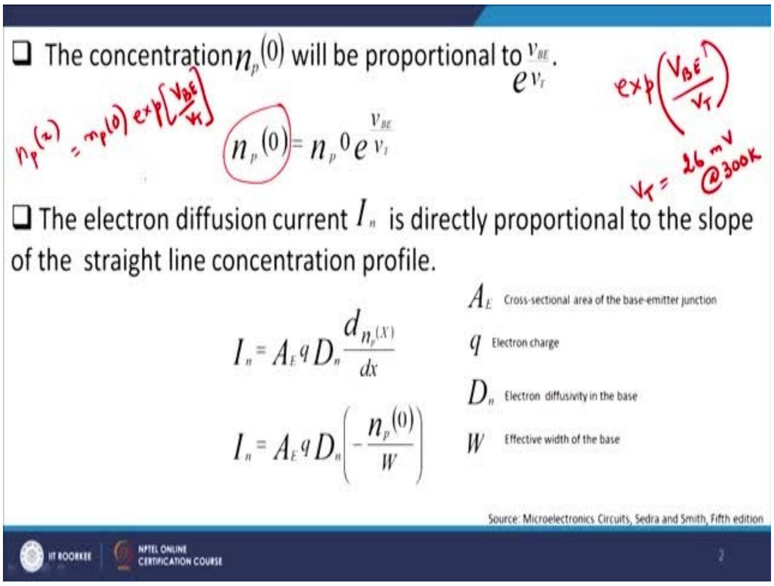

Today what we will be looking into is have a look into our basic fundamental principles which were left yesterday. If you look very carefully then, the minority carrier concentration will be proportional to e to the power or exponential V_{BE} base to emitter voltage and divided by the thermal equivalent voltage which is effectively equals to 26 millivolts. So V_T is equal to 26 millivolts at 300 Kelvin right 26 millivolts at 300 Kelvin which means that as V_{BE} increases based emitter voltage increases the value of $n_P(0)$, n_P0 is it should not be n_P0 it is basically the formula is n_PX at any point is equals to n_P0, e to the power exponential V_{BE} by V_T, please make a correction here. That it is n_PX will be equals to n_P0 exponential V_{BE}.

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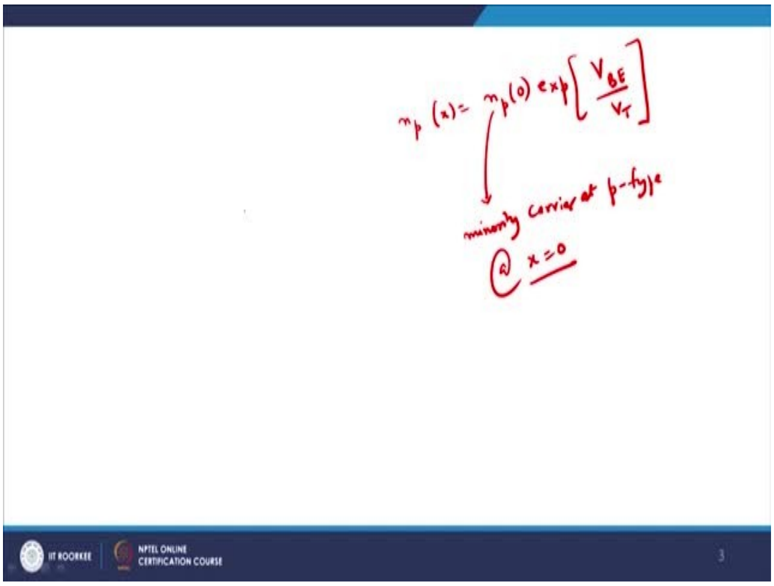

Now what does it tell me about this thing. So if it is n_PX equals to X is the distance from the base region n_P0 exponential V_{BE} minus by V_T as you can see from this concept or this basic idea n_P means n suffix p means this is basically minority carriers minority carrier concentration, carrier concentration at P type base at X equals to 0.

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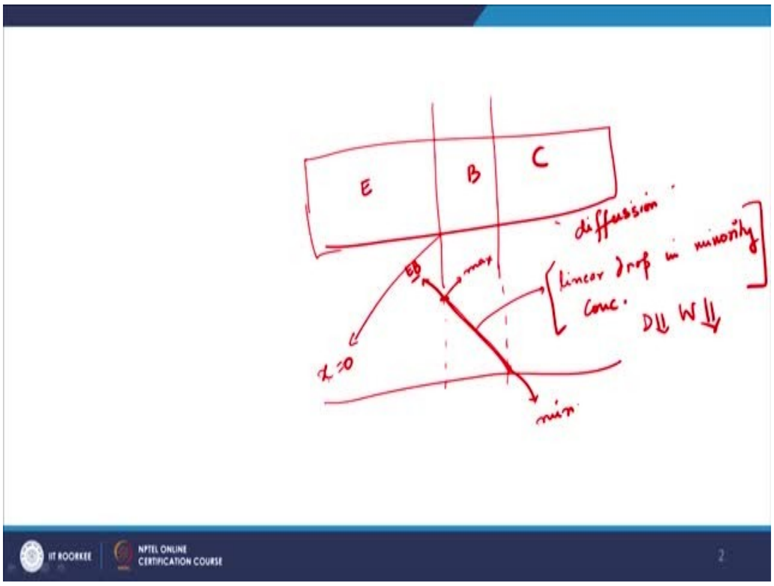

So X equals to 0 primarily means if you look at X equals to 0. It basically means this point. This corresponds to X equals to 0.

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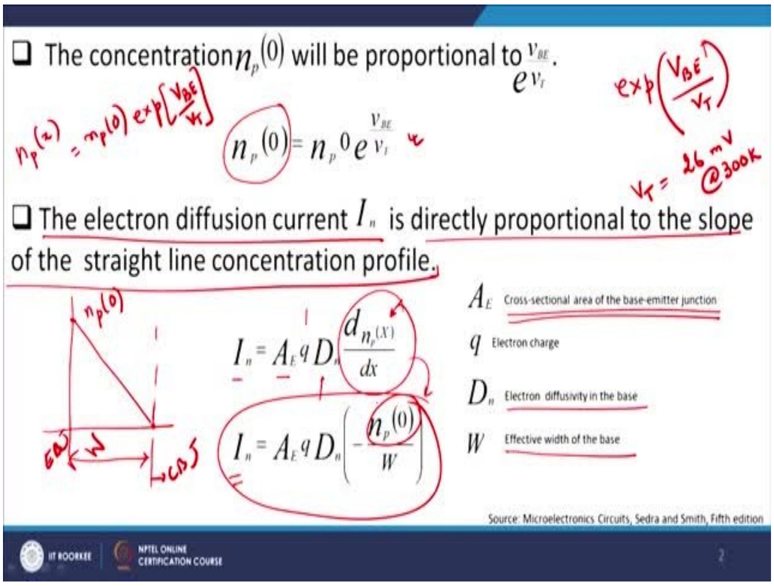

And let us see if we proceed forward it gives me an exponentially falling down, which means that though it is basically shown as exponential we approximate it as a linear fall concentration of electron as you can see. Therefore, if my V_{BE} would have been larger this is where the basic fundamental principles comes if

V_{BE} would have been larger I would have expected to see the value of n_pX to be also large right is it okay? For the same value of X which you see.

Because V_{BE} is typically large then I would expect to see n_pX to be also large because it depends upon the value of any particular point. Now the point which I wanted to make overall expression therefore is that if so therefore we define in this manner. Now electron now so, so you see so therefore what will happen is for the minority current carrier it will be basically a diffusion current which will be flowing in the base region. From a region of high concentration on the emitter base junction to region of low concentration or almost zero concentration on the base collector junction.

Now obviously this current will depend upon the difference of the concentration at the interface between emitter base and base collector. So as you can see here the electron diffusion current I_n is directly proportional to the slope of this straight line of the concentration profile which means that if concentration profile is assumed to be straight I can very well find the value current I_n to be equals to A_E multiplied by Q multiplied by D_n multiplied by d_P, dn_pX/dx right.

This is the standard formula for finding out the current where A_E is the cross-sectional area of the base emitter junction right, it is the cross-sectional area of the base emitter junction, q is the electronic charge, D_n is the electron diffusivity in the base and W is the effective width of the base and W is the effective width of the base. So you see I_n therefore if you take this equation, right and then this comes out to be minus $n_p(0)$ by W and the reason being very simple because we have assumed till now that the fall in concentration or the drop in the concentration will be almost a linear drop right, we have already assumed that it will be a linear drop.

So if it is a linear drop then it is very easy to find the slope of a linear graph provided you know this is basically your n_p0 which means the concentration of minority current carrier at the edge of the emitter base junction. So this is my emitter base junction, and this is my collector base junction right, this is my EBJ and this is my CBJ. Then this minus 0 assuming that you have reached zero value I get n_p0 and this is basically your W width of the base region right.

And that will give you the value of I_n in this case. Please understand one more important point here that in no way, right the depletion width on the emitter base or the collector base junction is influencing your electron concentration in the region of the base minority current carriers contribution. Because they will be nonetheless available at those particular points and therefore it will not affect the overall concentration of the minority profile in this case.

Right so this is what we have learned so we have learned this basic fundamental principle that therefore the current will depend upon the area A_E of the emitter and it will also depend upon the minority current carrier concentration at the emitter base junction, right. And we have assumed at this stage that the minority current carrier concentration on the collector base junction is approximately equals to 0. If it has got some finite value obviously this will be a lower this will be a lowered value and therefore I will get a lower current, right.

So higher the difference or higher the gradient between the emitter base and collector base in terms of concentration gradient I would expect to see a larger current to flow in this region. Right so we have learned therefore two or three important points out of all these discussion. And the first important point is that the diffusion current is independent obviously of the applied bias, it only depends upon the area, the diffusion constant and most importantly on the concentration gradient which you can see from this equation in front of you this equation right.

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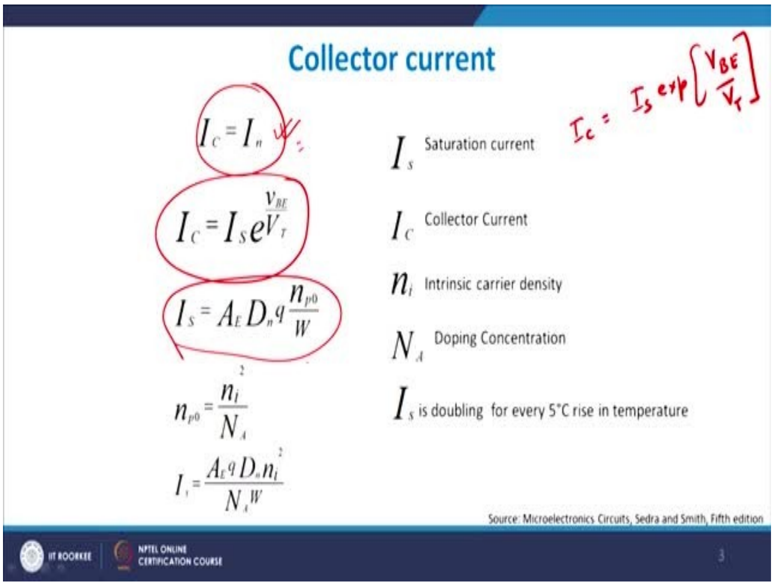

With this knowledge or with this idea we come to the next idea which is basically my collector current now assuming that you did have all the emitter charge carriers which were electrons and there was zero recombination in the base, I would expect to see all the electronic charge reach the collector side, right. So I can safely assume in that case that my electron current I_n will be equals to the collector current, right. So contribution in the hole is relatively small because it is a minority current carrier. And therefore the major contribution is from the majority current carrier which is basically the electrons.

And therefore I safely write down I_C to be equals to I_n, right and that is known as the basic equation which you see. Now I_C is the collector current can be written as I_Se to the power V_{BE} by V_{TE} so I_C equal to I_S exponential V_{BE} V_T, right. Where V_{BE} is the base to emitter voltage and V_T is the thermal equivalent voltage. I_S is defined as the saturation current, right. Very-very small current but it is the saturation current. Now, so I get I_S there therefore what we can write down I_S to be equals to this much I_S is the saturation current A_E into the D_n into q into n_p0 by W right.

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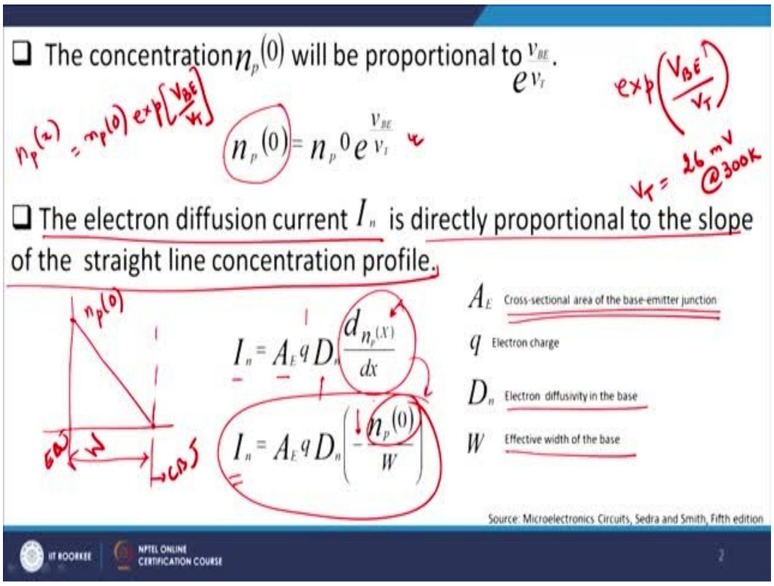

If you look at the previous slide you see you have a negative sign here. It is a negative sign which you see. And the reason is that the concentration starts to fall down as you move from X equals to 0 to X equals to W. So there is a decrement in the concentration and as a result there is a negative value which is been shown here.

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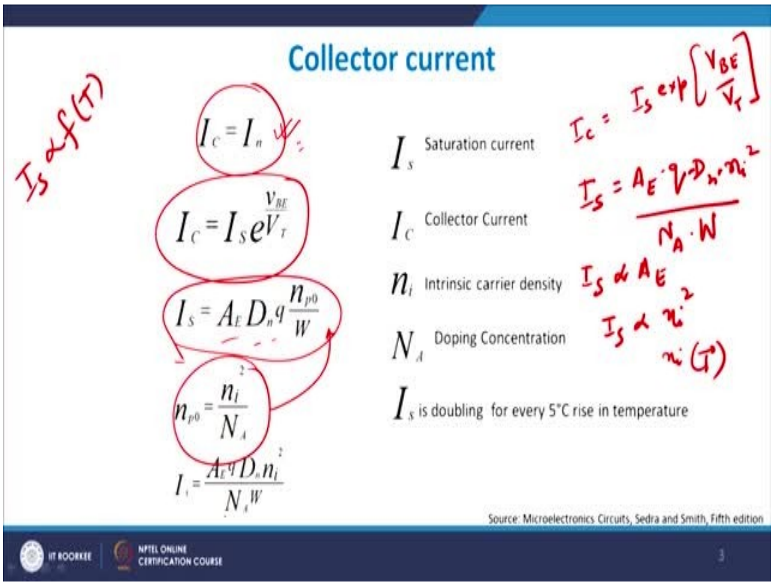

Now as you can see here I_S is given by this formula because I just replaced I_S by A_E, $D_n q$ n_p0 by W, again assuming 0 charge carriers on the collector base junction. Now from my earlier basic semiconductor physics theory I get n_p 0 to be equals to n_i^2 square by N_A. When n_i is intrinsic current carrier concentration and N_A is basically my acceptor ion concentration. And therefore if you take n_p0 and place it in this equation I get I_S to be equals to A_Eq, I_S to be equal A_E multiplied by q multiplied by D_n multiplied by n_i square divided by N_A into W, W is the, W is the width of the base region.

Which means that the I_S saturation current depends on the numbers of intrinsic carriers which actually doubles for every 5 to 10 degree rise in temperature, right. So you would expect to see a very large change in the value of saturation current in this case, second important point which you should be very careful and you can go through it you can see it that as the area of the emitter the cross-sectional area of the emitter increases your short-circuit your IS also increases. So I_S is therefore is directly proportional to A_E right and I_S is also directly proportional to n_i square.

Since n_i is directly dependent on is a function of temperature I can safely assume that I_S is therefore also a function of temperature right higher the temperature higher is the value of I_S which is saturation current in a standard NPN or a PNP transistor.

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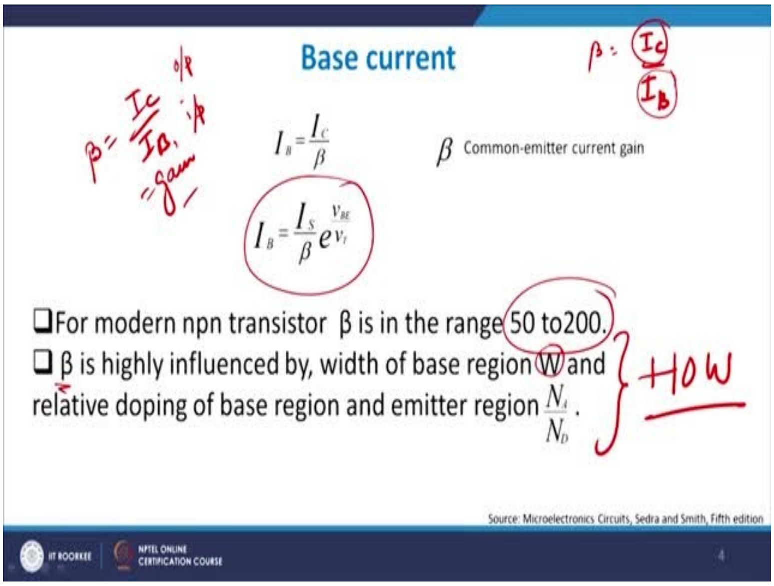

Now my base current therefore I_B is equals to I_C by β and therefore we define β to be as a common emitter current gain. Because if you look at β, β is basically I_C by I_B, right under the condition that you have a common emitter configuration so it is basically output by input and therefore this is also referred to as a current gain equation, right. Now, therefore again as I discussed with you just now I_B will be equal to I_S by β into e to the power V_{BE}/V_T.

Typically current model NPN transistors have β in the range of 550 to 200, right. The typical range of β is between, is typically between 50 and 200, right. And this range depends upon many factors apart from the material of the device it also depends upon the type of doping that has been done on the device, the level of doping which has been done on the device, right.

Now if β is high β is basically as you can see is basically I_C by I_B right. So if β is typically of the order of 500, 200, 300 so on and so forth. It primarily means that your collector current orders may be two orders or three orders higher than the base current and this is expected also and the reason behind this is that all the carrier concentration which was available to you from the emitter side, right goes towards the collector side, right and therefore recombination of electrons or holes on the base region is very-very minimally low.

When it is low your β value actually becomes typically large, because I_B value reduces drastically. So as you can see β is highly influenced by the base width and related doping of the base region and the emitter right so it depends upon N_A upon N_D, right. I suppose you will be able to find out why and how, right. I will leave it as an exercise to you to please understand why is it like that. That why β depends upon the base width region, region of the base region of the base. If it is very thick then β is relatively small if it is very thin then β is relative larger and so on and so forth, right. I give it as an exercise to you find out the value.

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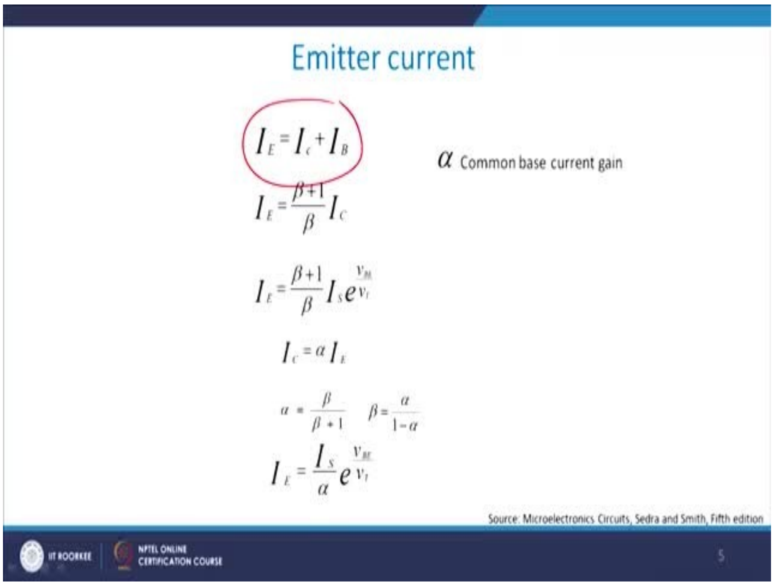

The Kirchhoff cannot be violated all of us know that over the years we have seen that. It cannot be violated in more sense than another. And therefore I can write down I_E to be equals to $I_C + I_B$, right. If you go back to your previous slides as far as this course is concerned then you will see that, or maybe let me draw for you.

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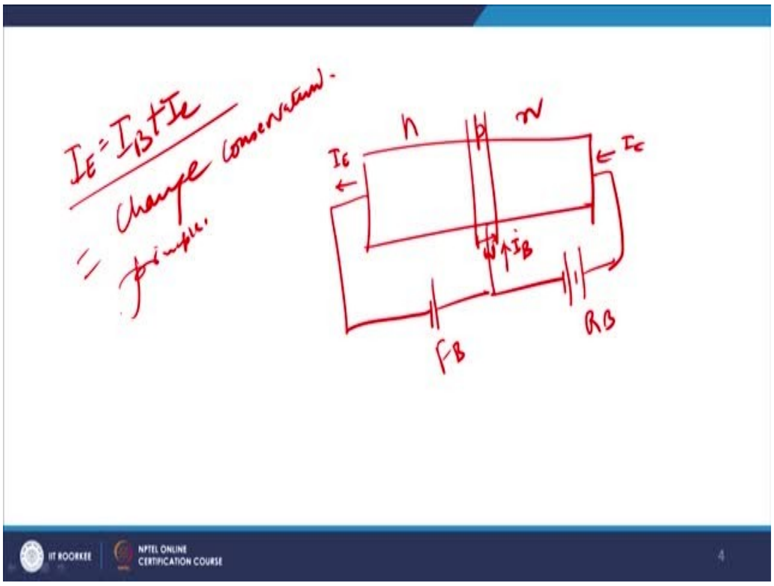

That if I have got a NPN or a PNP, if I have an NPN or a PNP then what I get from here is that this is forward biased and this is reverse biased and this is forward biased, right. And this is the width region where W is the width of the base region which is oppositely biased as N and P region. Now if you look carefully so it is an NPN. So if its emitter current is I_E this will be I_B, I_B and this will be I_C. So I can safely write down I_E to be equals to $I_B + I_C$ and this is basically charge conservation principle.

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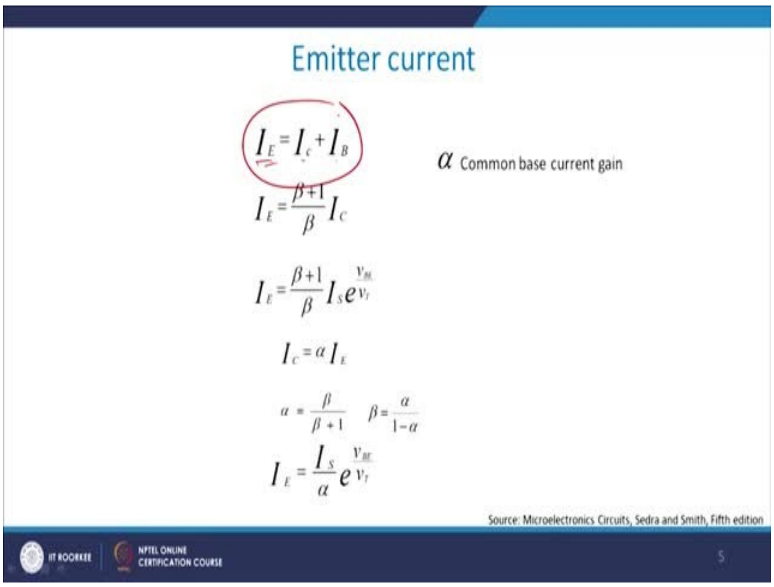

So this is basically a charge conservation principle, the charges is always conserved irrespective of the type of device you take irrespective of the material of the device you take. So I_E is equal to $I_C + I_B$ because you will be following the Kirchhoff's law and since you will be following the Kirchhoff's law the total emitter current which is entering into the system must be exactly equal to the total.

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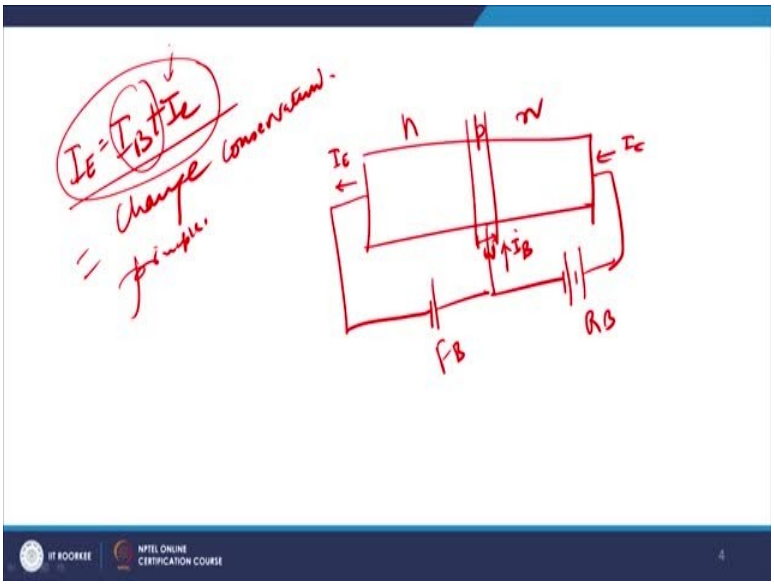

So if you look at very carefully I_E is equal to I_B plus I_C and therefore total emitter current in the system is sum of base current and collector current, right. And that is how you manipulate. So you try to therefore maybe control the flow of the collector current by increasing or decreasing the value of the base current right by changing the value of base current you can actually make I_C or I_E almost close to each other.

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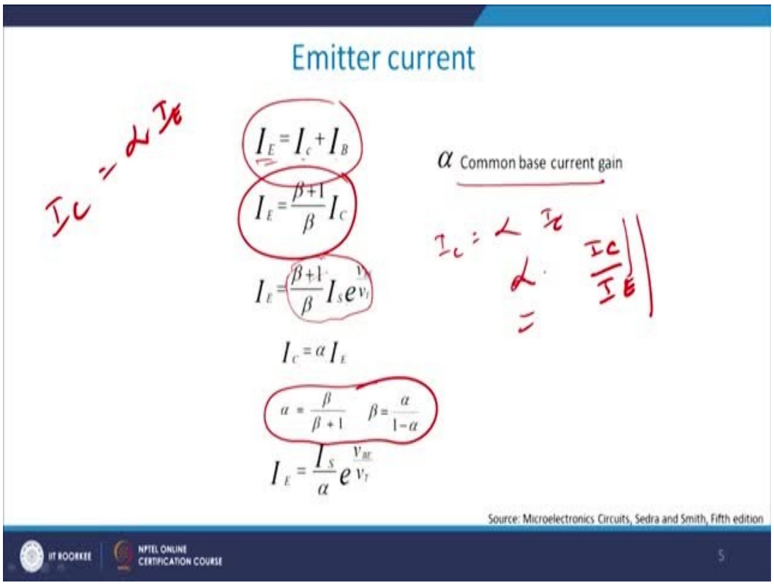

And that is the major study area which people are working. So I_C +, $I_C + \beta$ we know that I_E is equal to $\beta + 1$ upon β into I_C well that is the standard formula which people use, right. Then I_E will be therefore equals to $\beta + 1$ by β into I_Se to the power V_{BE} by V_T. And from here I get I_C equals to α times I_E. So all this I_C part which is basically your this part right is I_C, right, I get I_C to be equals to therefore α times I_E which is a known fact. α therefore is equals to I_C by I_E, right, and α is therefore referred to as common emitter current gain. Sorry α is known as common base current gain β is common emitter current gain.

And as you can see α depends upon the value of I_C and I_E which is understandably so because I_E is basically the total current being entering into the system and I_C is the total current exiting the system. So if you solve it, I get I_C is equals to α times I_E I get I_C to be equals to α times I_E. Which means that and this is quite simple and straightforward so α will be very close to 1. If it is 1 then I_C will be equal to I_E. In that case we are assuming that all the charge carriers which were initially originating from the electron or from the emitter side will actually terminate on the collector side and therefore I_C is equal to α times I_E, right. Two important equations to take care of α is equal to β upon $\beta + 1$ and β equals to α upon $1 - \alpha$. These two important equations are required for solving problems, right. And that is quite interesting problems solving which you can do using these two questions. Let me come to the last part of our talk and that is basically your large signal equivalent circuit model for NPN BJT.

Well, you see what we try to do is that when we have a device primarily in its initial stages of fabrication and testing we want to convert that device into an appropriate machine or a simple machine so that we can actually record its current versus voltage characteristics in a much better manner, right. And therefore we need to do a circuit level implementation of the device.

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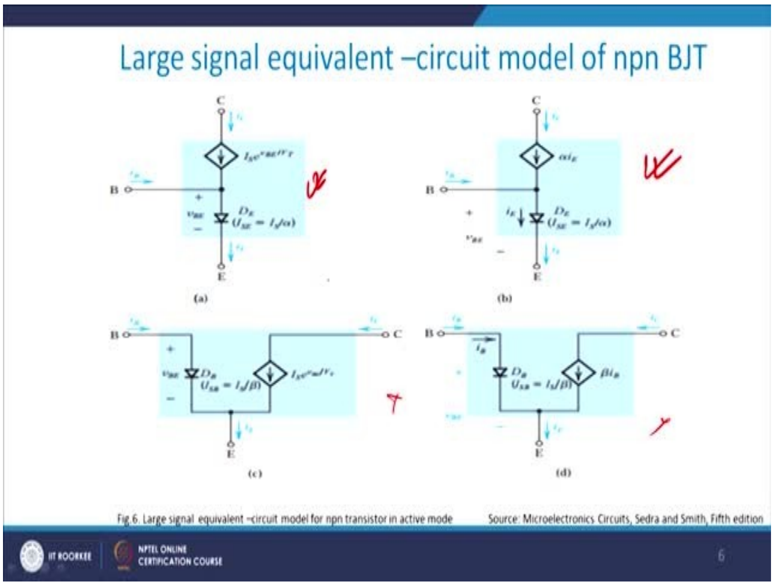

So this is basically a large signal equivalent circuit model of an NPN BJT. Which means that if you take a BJT right and place it in a large circuit domain then we can replace that BJT by these large signal equivalents, these large signal equivalents. This one as well as this one you cannot do this or this, but these you can surely present as an amplifier let us see what is what. As you can see if base current is the emitter current and base is this terminal. I_C is the collector current and C is the collector profile and E is the emitter terminal and I_E is the emitter profile or emitter voltage or current which is available here. Now you see if you look very carefully that whatever voltage source was there on the source side right we were able to give that voltage source and draw current. This current has same into the collector current so collector current is approximately same as the base current the emitter current the only problem is if the base width is large or the doping is relatively high then this assumption does not hold good, right. As long as the base width is small and your dimensions or your values are very very small in terms of potential, you will not be able to do this problem in a proper fashion.

Now, you see here if you look at the first picture or the first diagram here of the schematic here you will see that I have replaced the collector side by current source, right and that's true also.

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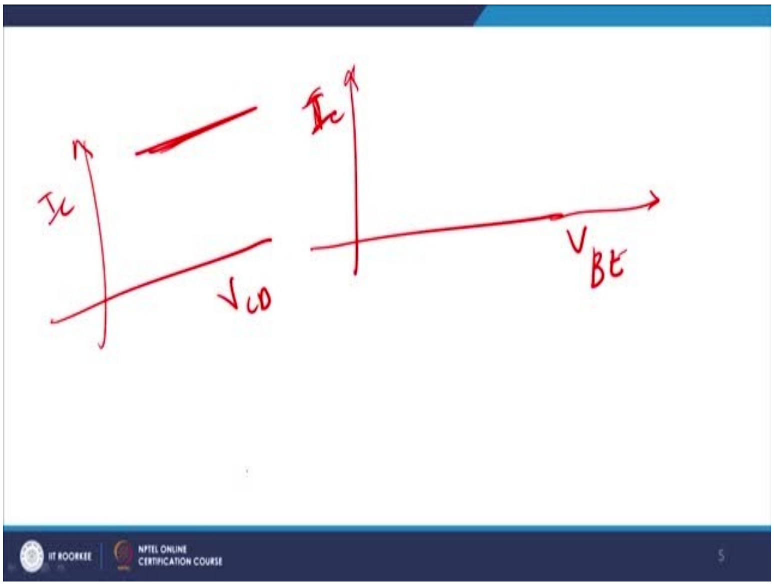

So, if you look very carefully once if you plot V_{BE} versus maybe if I plot if I plot V_{BE} versus I_C collector current most of the time it will be difficult for him or her to explain to me this I_C versus V_{BE} of any typical bipolar technology which you see. If that is the case we assume that we assume that that the base side potential is always fix it does not vary and therefore it does not vary to larger extent and therefore the collector starts to behave like a constant current source which means that even if you change the reverse bias of a collector base junction too much the current does not change too much.

So as I discussed in the previous turn it starts to behave like an ideal current source, right so if you plot I_C versus V_{CB}, I will almost get something like this a constant current source, right. Which means that I can replace the collector side by a constant current source if it is an ideal constant current source my output impedance will be infinitely large right and I will get almost fixed value of current even if I change the value of V_{CB} too much, right.

And therefore, you see this part which is the collector part is basically a controlled current source, right. So it is basically a controlled current source, who is controlling it the value of V_{BE} base to emitter current, right, that is controlling the collector current we have already discussed point and V_T is final equivalent voltage.

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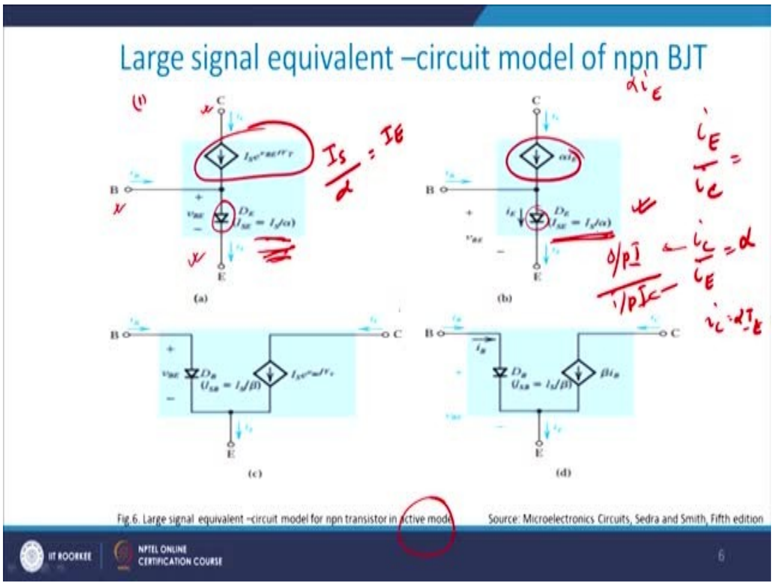

Now onto the emitter side this is the base and this is the collector on the emitter side we have a reverse biased PN junction why we have already seen this why. The reason being that at this stage since emitter base junction when you are using in an active mode because we are using this in the active mode emitter base junction will always be reversed biased, right because it will be reverse biasing the emitter base junction.

So once you reverse bias it I replace it by a reverse biased PN junction as you can see here and the current flowing through it is given as I_C is equal to I_S by α, right and that makes sense also where I_S is basically the saturation current divided by α is basically your I_E. And that is the reason this is therefore the large signal equivalent model of a NPN transistor BJT transistor.

Now the same thing if you look at this point which is this one you can see that it again at the basically collector base emitter and this model is again I_S by α as you can see same thing emitter current is available to me but now I can replace this by α times I_E because remember I_E by I_C is equals to sorry I_C by I_E is equals to α output current divided by input current is basically referred to as α.

And therefore I can refer I_C as α times I_E this is what people have done here and shown it here. This remaining exactly the same as the previous case, we will get this profiling done in a much more detailed manner. This takes care of approximately the whole large signal model equivalent profile of the model.

The diagram number C and D as you see you can do it by yourself is basically the common base configuration and therefore the base sorry it is not common base it is basically the base side is connected to input source and the collector side is connected to output source, right and from there I can find the value of C and D equations in a much more detail manner but typically what we have learned is basically large signal model of a NPN transistor.

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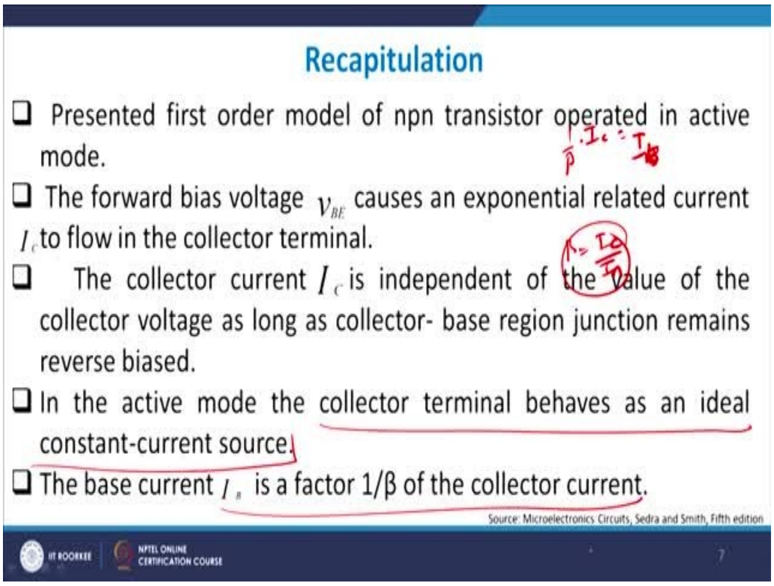

So let me recapitulate what we have learned till now, we have presented a first order equivalent NPN model operated in the active mode. Active mode is when emitter base junction is forward biased and collector base junction is reverse biased. Any forward bias profile or entity will always cause an exponential change in the value of current and therefore the collector current I_C is independent of the value of the collector voltage as long as the collector base junction remains reversed bias.

So as long as it is reversed bias I do not worry what is happening on the other side, on the other side means on this side of the collector. And we end up having therefore almost a steep profile in this thing. In active mode the collector current terminal behaves like as an ideal current source we discussed why. And the base current I_B is a factor of 1 by β of I_C so basically 1 by β of I_C is equals to 1 by I_E or 1 by β.

So I can safely write down it β to be equals to I_C by I_B for I_B is a base current, right. It will be a very small quantity but nonetheless the base current will be there which is available to you right. So this takes care of all your discussion here, I thank you all for your patient hearing. Thank you very much!