Microelectronics: Devices to Circuits
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Lecture 10: BJT as a Switch and Ebers Moll Model

Hello, everybody and welcome to the NPTEL online course on Microelectronics: Devices and Circuits. We start today's lecture with understanding of BJT as a switch and then conclude with Ebers Moll model of BJT. I will also give you brief introduction of Gummel Poon model, which is generally used in a SPICE, for SPICE purposes, which is a circuit simulator but before we move forward let me recapitulate what we did earlier. We had a look into the various small signal models available to us, out of which we had conclusively looked into common emitter, common base and common collective configuration.

We have also seen in common emitter, if you put an emitter resistance in series to the emitter port it increases the stability and decreases the gain. So that's what we have done in the previous lectures. We will start today to look into BJT as a switch and then maybe look into Ebers moll model at a later time, right.

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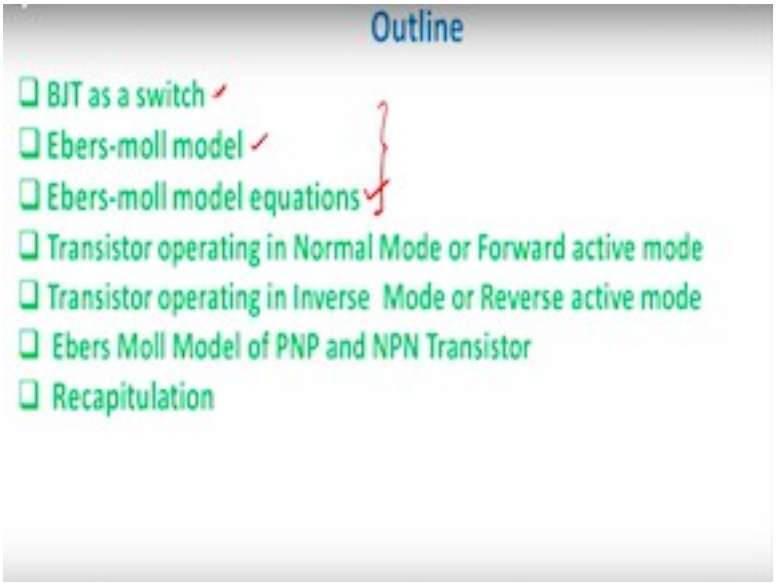

So just to, the outline of this presentation or the set of presentation will be; that we will be looking at BJT as a switch so it can be used BJT for the purpose of switch, right?, and the requirement is that whenever we have switch networks can we use BJT to do that, right, or can we use BJT to take care of those switch networks. We look at Ebers Moll model and its equations so, again as I discussed with you that small signal model and it is basically a circuit simulation model and therefore, we will be able to directly port these equations into circuits for the purpose of circuit simulation.

Then we would be looking at normal mode of operation of transistor which we have already seen in the inverse mode and then we will be putting the Ebers Moll model for NPN as well as PNP transistor, the recapitulate the whole thing once again, which means that we will be looking at into these detailed analysis once again. Now we will be looking first of all the BJT switch right, that is the first assignment, the first part in this idea. And they have been used for all your transistor-transistor logic, which is basically TTL. So let's see how a BJT can work as a switch.

Now, so we remember we all just now discussed and we saw that when the base emitter voltage goes beyond 0.7, which is basically for Silicon then we would expect to see it become forward biased and as a result it will emit large number of electrons if it is an NPN transistor and the device will be in on state, right, and it will be in off state provided the base emitter voltage is lower than 0.7 as such. So if you are able to make a transition of the base emitter voltage from 0.7 upwards to below, I can move from saturation to cut-off and vice-versa.

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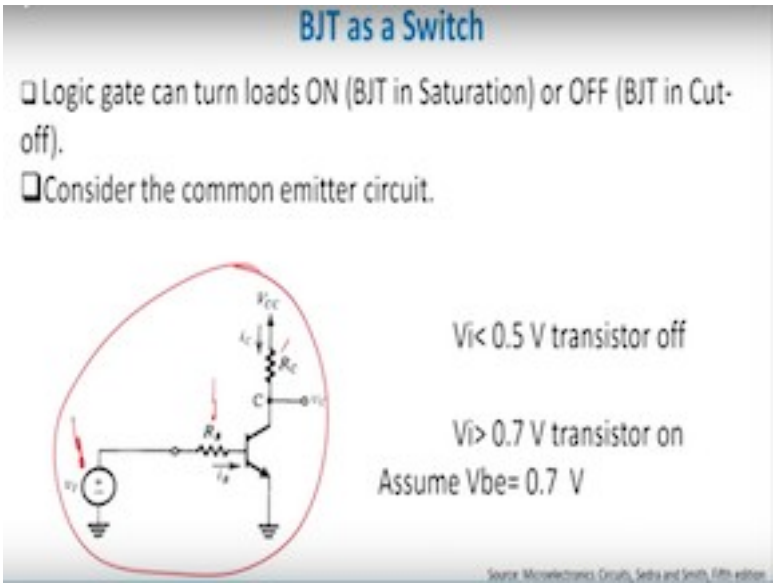

Consider the circuit which you see in front of you, this circuit, right? Where I am giving an input voltage V_i, right. So this means that we are giving a input voltage that is V_i and this will be a sum of DC and AC bias. DC bias will be helpful for choosing the Q-point and AC bias will be actually giving you the switching characteristics. So whenever my, this R_B and R_C, this R_B and this R_C are the resistance which is there in the base side and the collected side of this BJT and there so that excessive current does not flow through BJT and burnt it out.

So if let us suppose that this gets shorted R_B was shorted, then if your source which is the voltage source, a DC voltage source because of some problem or other gives you a large current suddenly then the chances are that the BJT will burnout and therefore in order to ensure that it does not burn out we give a R_B value here. So this R_B R_C and the β of the transistor fixes the, fixes up the Q-point of the transistor so it gives me the fixed value of V_{CE} and I_C, right? It gives me that value, where should you bias so that it acts as a switch that we need find out how do you bias it.

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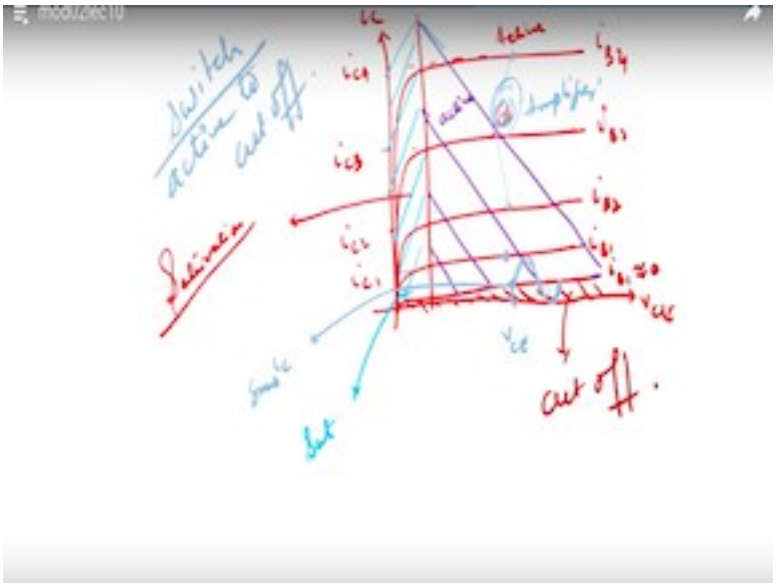

So if you plot the common emitter configuration for various values of V_C vs I_C if you plot, right. Then this is for the various value of I_B, I think, right. So this is i_{B1}, i_{B2} and so on and so forth, i_{B4}, i_{B3} and this is basically i_C and this is your V_{CE}. So this will becomes your i_{C4}, right. This becomes your i_{C3} this becomes your i_{C2} and this becomes your i_{C1}. So this is your saturation region almost and this is your active region. Active region, this is your saturation region. So suppose you have a current source which is somewhere here.

So typically, for, to be used as switch, if you bias it somewhere here, let us suppose, which we generally do if you are using as an amplifier. Suppose use a Q-point. Then you, so if you look at the Q-point then, I will just give you the reason, so this is your let me show you using different color maybe and I will just show you the different color combination and may be let me use this, now this part, right, this part, which you see as I discussed with you is basically your saturation, right. Now this part, right is your, sorry this part is your active, this is active and below this part, below this part, this is all cut-off and this I_B is approximately equals to 0 or very close to 0. So if you bias your device in such a manner that you end up having, your Q-point is somewhere here then you can understand that even if I give small signal input I will not be able to cross the cut-off point. So the positive half cycle is surely no, no region, negative half cycle also i_B will just come from i_{B4} to i_{B2}.

So if you bias your device at this Q-point, you will never be able to work it as a switch but then you can work it as a good amplifier. So the good idea is that if you want to use it as a amplifier bias is by using external DC sources in such a manner that it is somewhere in the middle of the active region, not very far from the saturation is cut-off. You want to use it as a switch then bias it somewhere maybe here or may be somewhere here and then in the positive half cycle agreed there nothing will happen; but the negative half cycle you will enter into cut off, right. So when your input is moving in the negative half cycle, the output is also going to the negative half cycle then you enter the, into cut-off limit, right.

So you can do cut-off but to do that you have to your V_{CE} maybe, typically large but then you have to ensure your i_C to be small. So this i_C is small i_C. This small i_C can only be done if you have i_B small. How do you do that? How can you make your I_B go very-very small, well very simple and straightforward; if you look at this point make, your R_B very large? So when you make your R_B very large you ensure that your, i_B falls down drastically, right and then as a result you will have a much, much lower value of i_B available with you.

As a result you will be able to go into cut-off. Now, the idea therefore is that when you go from therefore active to cut-off, right, without going into saturation we define that to be as a switch, right. So we define switch to be from active to cut-off, and then vice-versa, so from the cut-off to active again you want to go to it. Now you will, obvious question ask is can BJT be used for high frequency application which means that can I use this switch when the input frequency is typically very high? The answer is it is difficult; it's pretty difficult and the reason being that how does one go from on to off state?

We go via changing the emitter base junction from forward to reverse bias and then from reverse to forward. Now there is always a finite amount of time which has to be given to the diode, PN junction diode in this case such that you allow for the systems or the charge carriers to come back to its original position; this is known as reverse recovery time, right. We will not discuss any further than this case but I will give you a brief idea what I was talking about.

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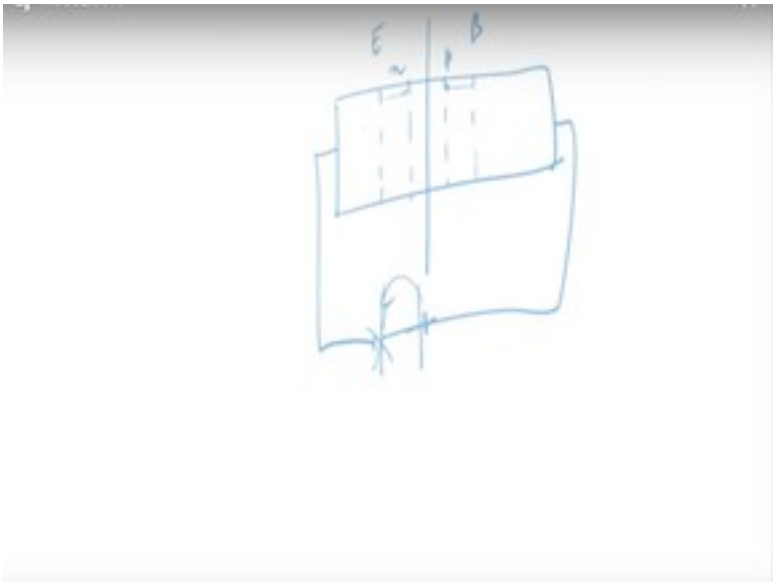

So let us suppose I have PN junction, right, so assume this to be as emitter and this to be as base so I have got NPN so this is N and this is P let us suppose. I have a depletion region here, now what I do is I first of all forward bias it, so I do like this, as I do it current flows in this no problem, then what I do is I have to reverse bias it, what I do? I just remove this part and I add something like this... Once I reverse bias it this again, the current stops because the depletion thickness becomes quite large and there is no current.

Then we again go from reverse to forward, right. Once I do it then this has to go down; this limit has to go down. How it can go down? Provided the charge carriers from both sides move across the boundary metrological boundary and thereby form the, remove the depletion region. This requires a finite amount of time and that's the reason you have to give sort of a minimum cooling period for the diode so that it basically moves from on to off state and off to on state.

So…so… typically BJT cannot for this simple reason, there are other reasons also it is one of the reason why you cannot work it at a very, very high frequency, right. At typically gigahertz or terahertz, you can-not work with BJT; the reason is you do have problem that a minimum amount of time has to be given to the transistor for the BJT for the recovery of the time, right so that is reason is always a limit to the frequency at which the BJT can work as a switch.

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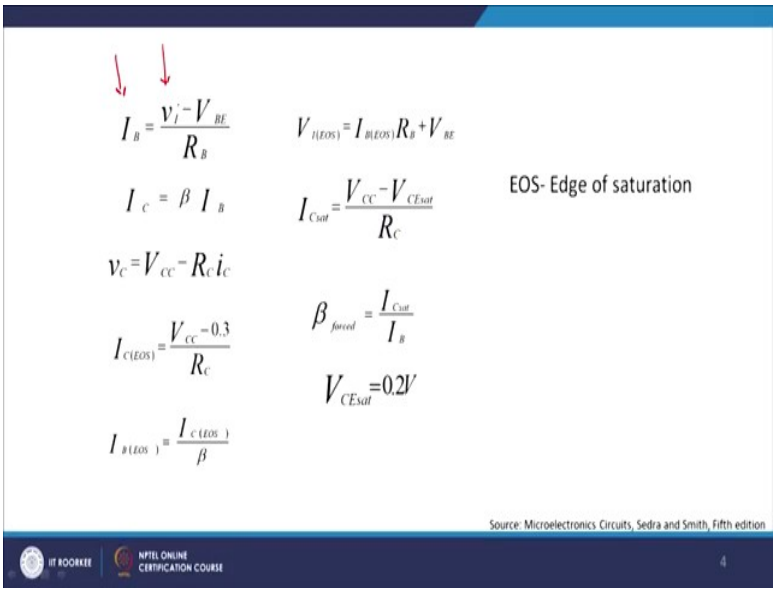

So if you look at this figure or in this equation you can see that the I_B, the base current can be given as V_I , V_I is the input voltage minus V_{BE}, minus V_{BE} why?

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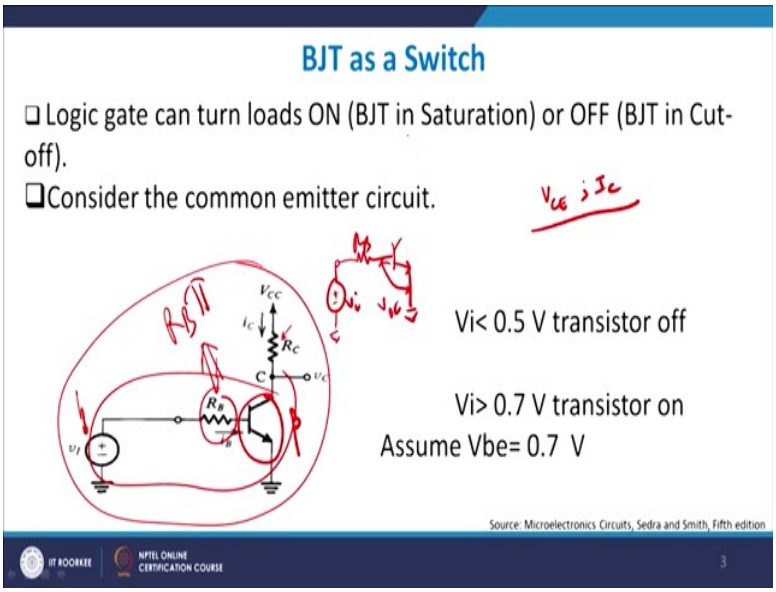

Because this is the, so I am concentrating at this place, right. So it is something like this now that I have R_B, right and then this, right and then, you have got V_I. So V_I minus V_{BE}, right, divided by R_B is your I_B.

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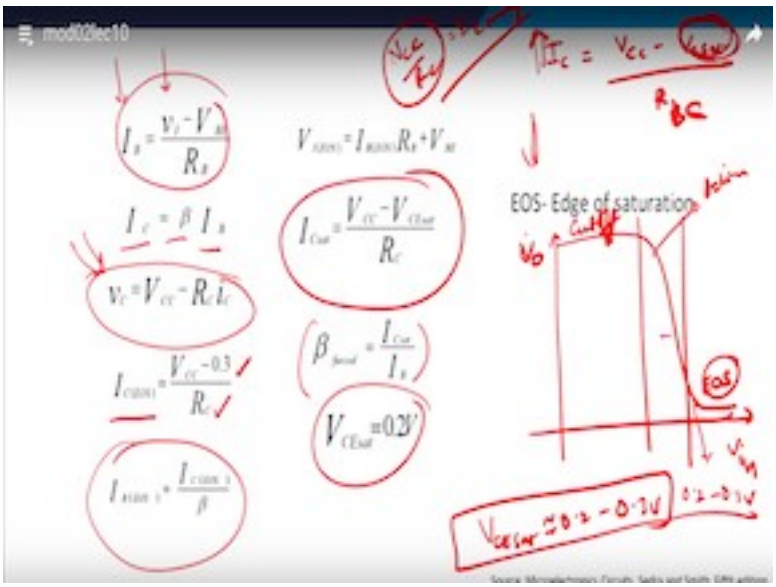

So this is your I_B, right? So I_C will be equal to β times I_B; a straightforward way of looking at it and therefore, if you multiply this I_C with R_C and then V_C we will be equals to V_{CC} minus $I_C R_C$ and I will get from this equation the value of V_C which is the collector voltage available with me. Therefore as you can remember I_{CSAT} from here

also you can see, I_{CSAT} will be equals to V_{CC} minus V_{CESAT} by R_C. Now I will ask you, where is this *SAT* or from where I can get the *SAT* value?

Remember, if you remember the voltage transfer characteristics which we are studying right, and we were studying like this and then it was going like this and we defined this to be my active; this was active, this was cutoff and this was, sort of edge of saturation. We started with saturation from here and this was *EOS* or the edge of saturation where you have a negative cut-off with you. So this is your input and this is your output, right. So this was active region, this is the active region and this is the edge of saturation.

So, I get this is approximately 0.2 to 0.3 voltage V_{CESAT}. So V_{CESAT} is approximately equals to 0.2 to 0.3 volts, fine. With this knowledge I say that I_{CSAT}, which is the saturated collector current will be equals to V_{CC}, right, minus V_{CESAT} by R_C, fine, which means that it is basically V_{CC} minus V_{CESAT} minus R_C. V_{CESAT} will be typically very small, 0.3 maybe. So I get V_{CC}, so if you look at edge of saturation minus 0.3 divided by R_C, right, I get V_{CC} minus 0.3 divided by R_C and therefore, I get V_{CESAT} approximately if I say 0.2 and I get β forced is equal to I_{CSAT} by I_B and I_B equals to I_C by β, so that is very straightforward way of looking at it.

But I wanted to make it clear write one important point here, that therefore I_C if you remember is nothing but V_{CC} minus V_{CSAT} remember divided by R_B, base current, right. R_B, no R_C I think, sorry! R_C, right..? So the obvious question asked is how can you maximize I_C because then only you get large currents, is that if you make this one as close to zero as possible, right?

So typically the maximum value of I_C will be V_{CC} by R_C, fine, that is the maximum value. So I_{CMAX} can be written as V_{CC} by R_C, right, and that's the reason you always get, for example in this case; when you have to have a switch you have to ensure that the current actually moves from, the I_C value moves from a relatively high value to relatively low-values when we move from active region to edge of saturation. In the edge of saturation the value will be relatively very, very small, right. So this is for you to keep in mind as far as switching is concerned or switching understanding switching is concerned.

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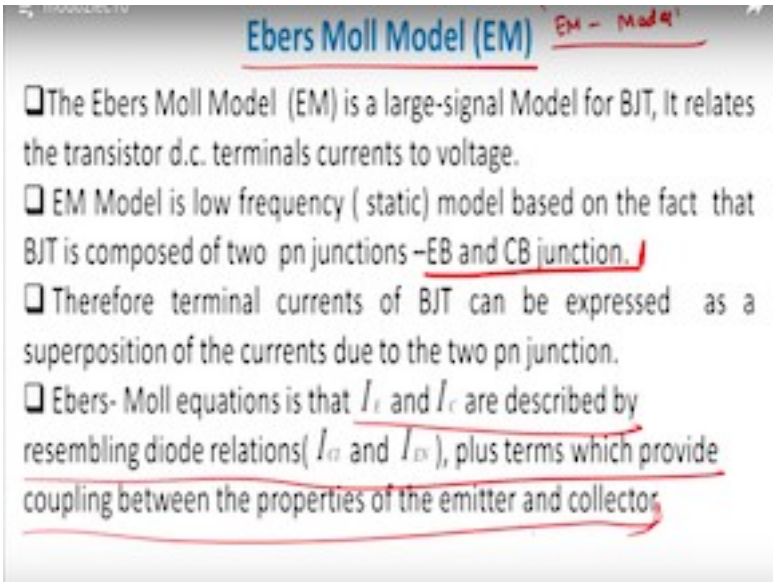

We now come to what is an important terminology that we use in the bipolar technology and that is known as the Ebers Moll model, right. This is known as Ebers Moll Model also referred to as *EMM* or *EM* model, right, by two scientist Ebers and Moll. Ebers Moll model is a large signal model for BJT unlike the previous models which is T and π, this basically is a large signal which means that we don't restrict ourselves to small changes in input but we are looking into large changes in the input and then try to predict the output voltage or current from this *EM* model.

This *EM* model is basically a low frequency. So it is not even high frequency model, it is a low frequency model and what it does is that it takes care of BJT as a two junction device. So it's an EB and CB device. So I have got two junctions emitter base and collector base junction. Right? Therefore what the idea of Ebers Moll was that therefore, everything can be broken down into set of two currents, one current flowing through emitter base another flowing through collector and base, right. These two things and also two other component, which depends on the emitter base junction and collector base junction.

Therefore told that the total terminal currents I_C, I_B and I_E will be a weighted sum or superposition of these two-junction currents *EB* junction and *CB* junction, so that's what we are saying the Ebers Moll equation is that, that I_E and I_C are described by resembling diode relationship plus, the coupling between the properties of emitter and

collector, right. So these are the reasons why we do an Ebers Moll model as such. Let us see how Ebers Moll model looks like, right.

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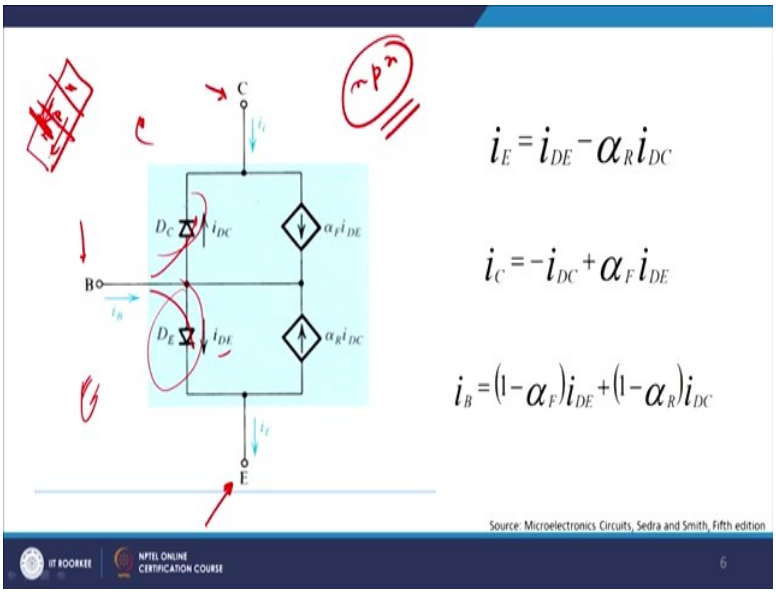

Now look at the, so this is the, it is basically a three terminal device, I have a base, I have a collector and I have an emitter here, *E*, is the emitter here and. So it is basically again as I discussed with you, it's a three terminal device. Now I have current I_B flowing into the base collector I_e and I_e, so it is basically an NPN transistor design, which we are trying to do. Now as you enter this point, this side is emitter, right and this is collector. So this is emitter and this is collector, right.

Now if you look very carefully this is basically emitter base junction, this one and this is collector base junction, right. Emitter base junction is defined by a diode, right, whose one side, p-side is connected to base, because it is NPN, so this is base, so this will be diode equation, right. As a result you will get a *DE*. So why do we get i_{DE} here, I will just show you, why we get it.

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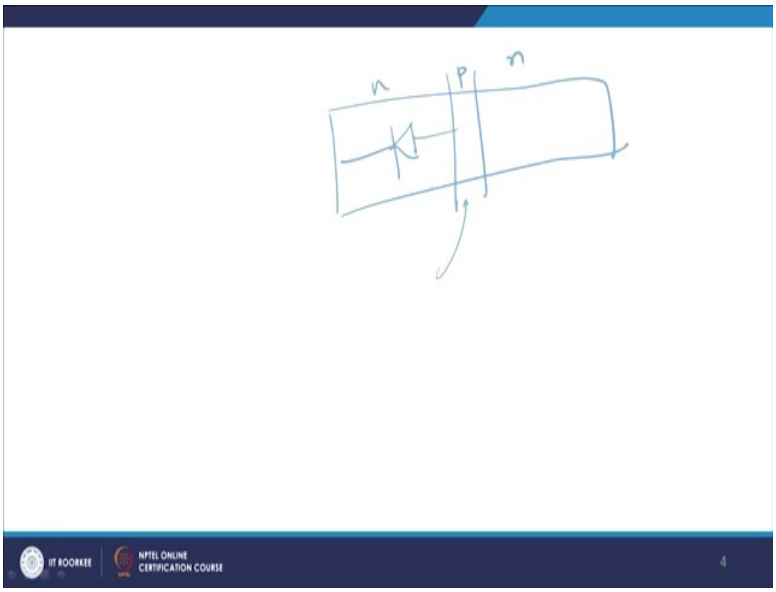

So if you plot a NPN and if you look from this side from the base side, right. Then it will be, if you want to forward bias it, it will be something like this, right, and that's the reason we are showing you that by this statement here.

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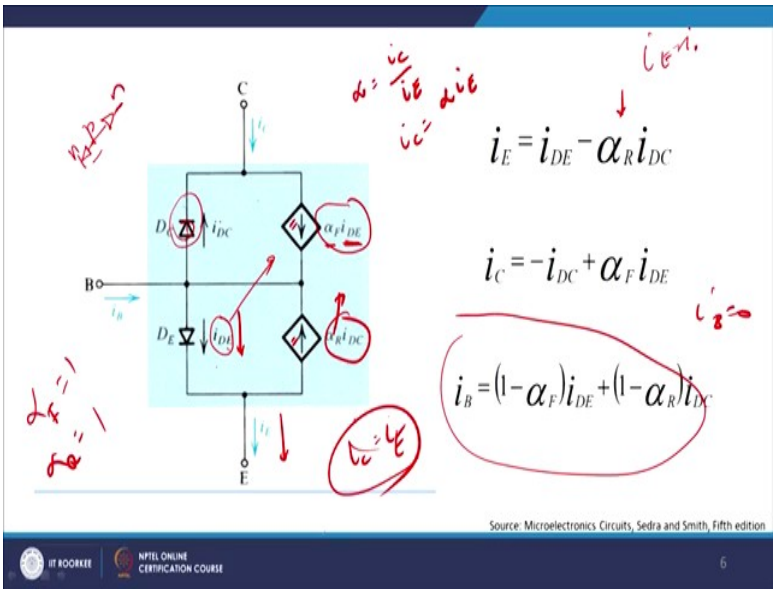

So this is the reason we see i_{DE} here and base to collector is shown in this manner, because it is an NPN so the diode will be in this direction and it will be in this

direction, that is what we are seeing, right. So both P are connected towards base and both N connected toward collector and emitter.

What is α_F into i_{DE}, right. α_F into i_{DE}, α_F into i_{DE} is emitted current, so i_{DE} is this one emitter current that you see, if you multiply this with α you get. So remember α was equal to i_{CE} by i_E, fine. So I can define i_C to be equals to α_{iE}, that's what you have done. So α_F forward current multiply i_{DE}, right, so this you multiply with this one you get this one and similarly α into i_{DC} will give you the value of collector current, right.

So therefore see, therefore you see the direction of the collector current is also and the emitter current is also shown in this manner and this manner, right and you can predict the reason why is it like that for all practical purpose. So I get from here, i_E which is looking from this side i_E equals to i_{DE} which is, so i_E is this side, i_{DE} is this side and since i_{DC} is the opposite direction I get minus α_R times i_{DC}, you see α_R is basically your this thing, reverse current again, right. And i_C will be equals to minus i_{DC} plus α_F into i_{DE}, minus i_{DC} because the direction of current is reverse.

Therefore I can finally find out since i_E is equals to i_B plus i_C, i_B will be 1 minus α_F i_{DE} plus 1 minus α_R into i_{DC} fine, so this is the value of i_B which we get as such. So therefore if you say, α_F and α_R both are equals to 1, then i_B equals to 0. And therefore i_C equals to i_E, fine. But this is not true because α_F which is a forward gain and α_R which is the reverse gain will never be equal to each other, they will be a large difference between the two and therefore, this inequality that i_B is equal to 0 will not hold good, right. And that is almost a sure shot sort of a network. So using that network which we have just now saw, we can write down the basic equations of Ebers Molls Model.

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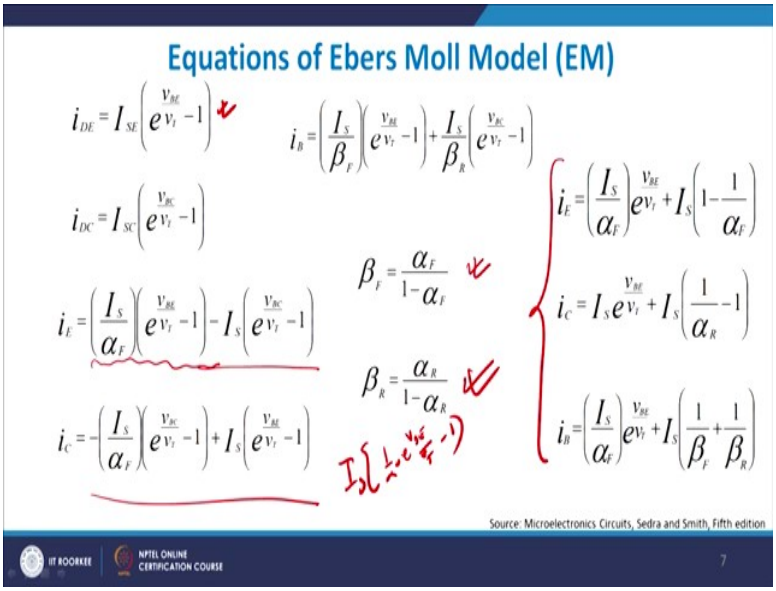

The first equation is of course as we have discussed is this one, which is i_{DE} equals to I_{SE}. V_{BE} $e^{\frac{V_{BE}}{V_T}-1}$. i_{DC} is equals to I_{SE} $e^{\frac{V_{BC}}{V_T}-1}$. Then i_E, if you look very closely is this is basically your i_{DE}, right. And therefore I get this minus this, right. And then I get this minus this we get, then β_F, forward and resistance and negative resistance β_R and then we get from these equations the values of i_E, i_B and i_C, right.

And we see that, if we look very carefully here that base to collector junction is always in a forward active region. V_{BC} will be quite large and negative, right. As a result this will all vanish. So I will be only left with minus plus I_S, fine. So I_S by α plus I_S so I will get I_S common, so I will get I_S common, Right I get 1 by α multiplied by $e^{\frac{V_{BE}}{V_T}-1}$. Right, we can get something like this for our understanding purposes. Same thing happens if we take negative value for your Ebers Moll Model.

Ok, so we have therefore understood the basic fundamental principles of the Ebers Moll model. We have also understood how Ebers Moll model work. We have also understood how does a BJT, Bipolar Junction Transistor can be removed and we can replace it by its corresponding model file and provided we are able to sustain these equations in the model, right. And we are able to achieve a sustained value of these model files. Before we move forward to inversion this thing, let me give you a Ebers

Moll model for NPN and PNP transistor. Ebers Moll model for NPN and PNP, this is basically a PNP, right.

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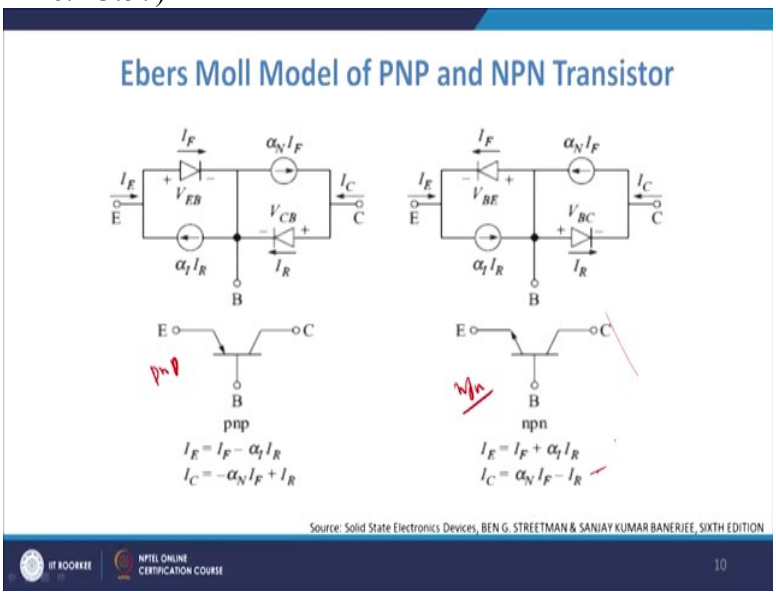

This is basically an NPN, right. NPN is relatively easy to handle, so I can do it, I_E is equals to I_F plus $\alpha_I I_R$, right. Similarly I_C can be written as $\alpha_N I_F$ minus, because it is a reverse bias, minus I_R, right, because in negative side there is no gain which is available at this transistor at NPN but for PNP you do have a gain available and therefore this comes out to be like this, right, and I get α_{IF} plus α_{IR} as the value of the base collector current, right.

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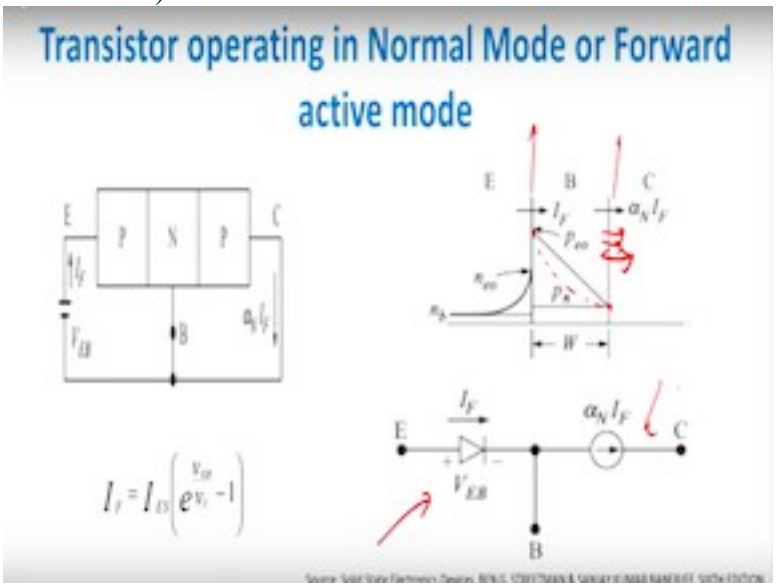

Now we have already discussed transistor operating in normal mode or forward active mode. Just to give you a brief insight what will happen in reality we will see that, as I discussed with you that minority current carrier will actually go down linearly from emitter base to collector base and it will go to such a low value at almost near this thing will go to zero because, the collector will be removing all the electrons from the junction. As a result will go to zero.

So that is quite difficult but since you do have recombination in the base side therefore this will ideally will not be a straight line but will be slightly bend in this manner and as a result because of the recombination, the result you will have a bending parameter there. So this, if you see at this model, this one, it is emitter base collector. So in the emitter base collector this V_{EB} is nothing but the base to emitter forward resistance. I_F is the forward current and α_N into I_F is basically the collector current, which is to be developed or which has been developed, right.

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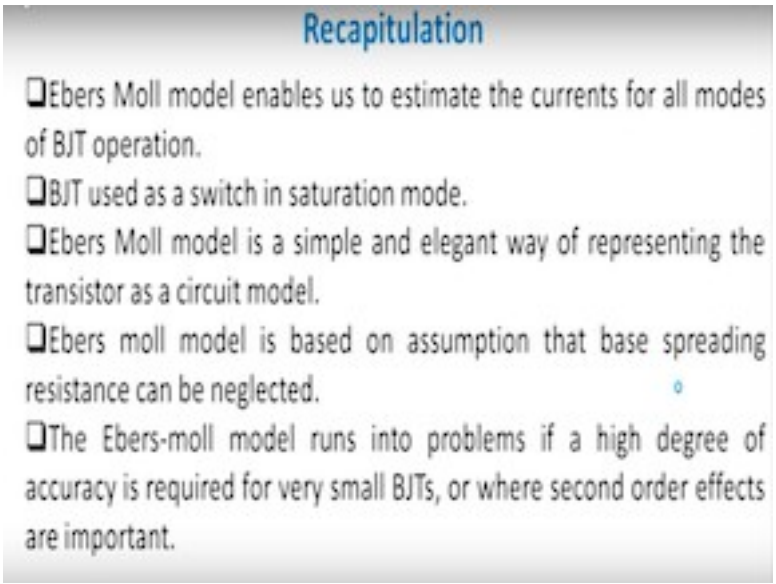

With this idea let me recapitulate what we have done in this module. We looked into Ebers Moll model and tried to estimate the currents for all modes of operations of BJT. Please ensure that the current will be typically very high in active region, almost zero in the lap region. It will be moderately good near the other regions, right. So in

the saturation region it will be typically very, relatively high but fall very fast, active region it will be typically very high but remain in that high position for quite a long time until and unless an external force is pulling the node down and cut-off is region where the effective current is approximately equals to zero.

Please take my mind reads effective resistance and approximate resistance goes to zero. Real resistance might not even go to zero at any point of time. So as I discussed with you Ebers Moll model is an elegant way of expressing a circuit, right, and then what we have neglected in Ebers Moll is, we have neglected the effective base with model, right. So please keep this in mind when we do the next time, we will be using the effective base model which means that the, we remember when we have reverse passing the collector base junction.

The effective base width was reducing, right. So it was going down, and as a result there was certain issues which were formed down, which were not addressed by the Ebers Moll model, right, and therefore all your second order effects and everything which is emanating from Ebers Moll model need to be questioned and we need to look into those facts in a detailed fashion.

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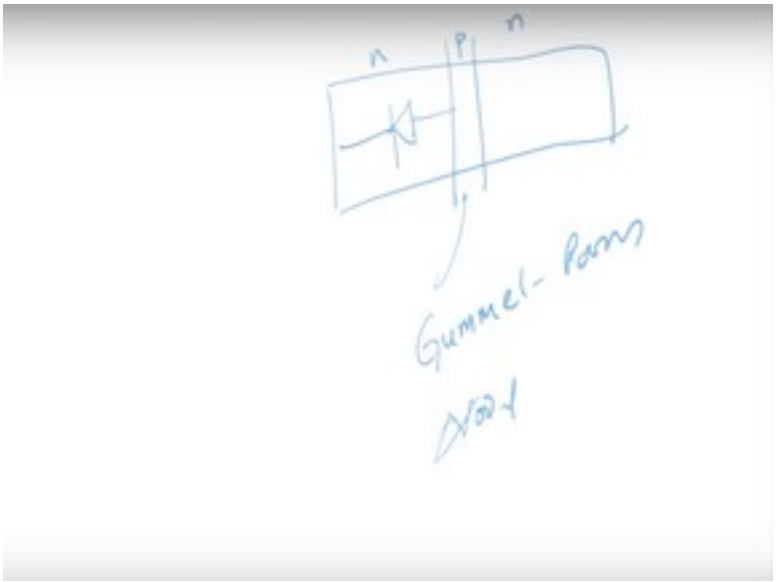

So Ebers Moll model actually fails when you want to have a second-order effects coming into picture, right. So Ebers Moll model does not work very good in that case

when you have second order, in that case what works is basically my Gummel Poon model. You should look at Gummel Poons model and this is much more robust model at high frequency, at a very high frequency domain, right. And this is what we have learned from our previous understanding of statements, right. Ok, with this let me also therefore, we have therefore taken care of two important points in this lecture.

The first point is that we have looked into transistors, the transistors BJT as a switch, so I can switch active to cut-off and cut-off to active, vice-versa by fast movement of an external peripheral source. We have also seen the Ebers Moll model and how can it be integrated with circuit analysis. We also looked into basic Gummel Poon. Gummel Poon will come to later on if time permits but we have looked into those facts and we were able to sustain a much better design for a BJT base design, okay. Thank you very much, thank you.