**Microelectronics: Devices to Circuits**
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Lecture No 04
BJT: Operation in Active Mode Circuit Symbol and Conventions - I

Hello everybody and welcome to the NPTEL online certification course on Microelectronics: Devices and Circuits. In our previous lecture we have understood the basic functionality of a transistor and why is it basically working as it should be. We have also understood the various numerical formulae's used for finding out the current flowing through the circuitry.

We have also gathered a position or we have also understood or appreciated the role of minority current carrier's in the NPN or a PNP junction. We have also seen that it can work in four different modes of operation for the purpose of switching as well as for amplification purposes.

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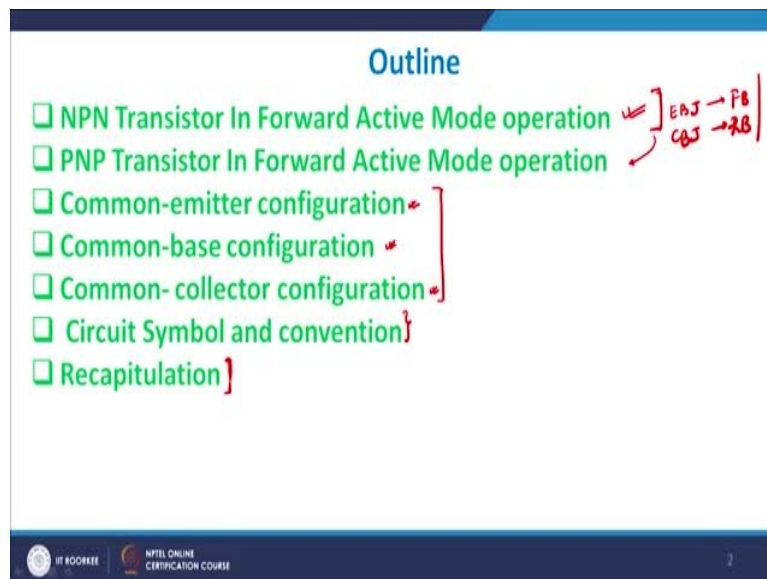
In this lecture we will be looking into its operation so the name of this lecture or the title of this lecture is Operation in the active mode, circuit symbols and conventions. So that is the lecture topic and what we will be looking into in this module or in this lecture is basically NPN in forward active mode. So once you have understood NPN in forward active mode we will be easily able to understand PNP in forward active mode, right.

Forward active if you remember is when your emitter base junction is forward biased and your collector base junction is basically reverse biased, right. So this is your forward active

mode junction which you see. We will also look into three configurations of working of this transistor which is basically common emitter, common base and common collector.

And then we will see some of the conventions and circuit symbols used and then we will recapitulate what we have learned across this module. Now if you remember in the previous discussion or in the previous understanding we had encountered two important terms one was basically known α and other one was basically known as β, right.

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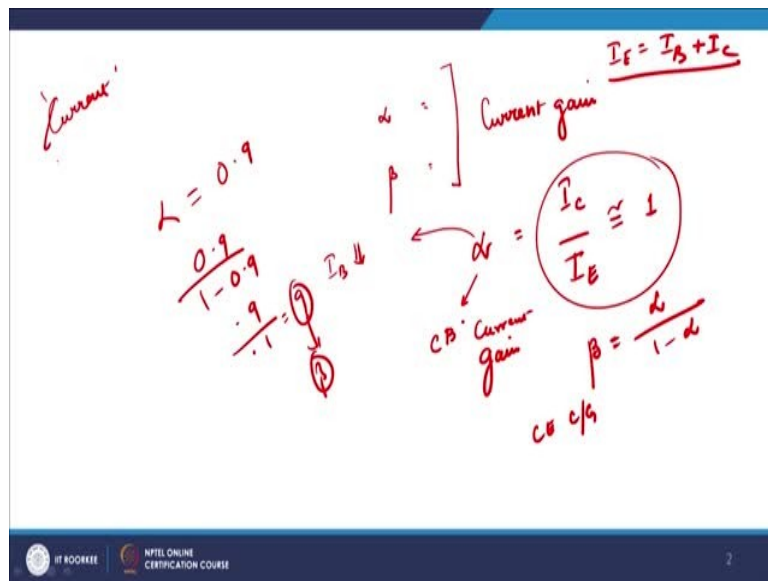
And both were if you look very carefully both were actually current gains, right, current gain. α was defined as I_C by I_E so this is basically your common base current gain current gain. And if you look very carefully the numerical value will be very close to one. And the reason being that I_C is approximately equals to I_E because I_B is very very small assuming that we already have this Kirchhoff's this is already there. I would say this to be very close to 1 right α to be very close to 1.

Typically β is known as common emitter current gain and it is referred to as α upon α - 1 so that is what we get as β here so it is basically α multiplied by 1 - α. So if you take α to be equals to 0.9 approximately then I get 0.9 by 1 - 0.9, so 0.9 by 0.1, I get approximately equals to 9, right. Is this clear conceptually so I get 9 so this β which you see in common emitter current gain.

So you see we will discuss this as we move along. But primarily you see that we have tried to find out in our previous discussion the current gain because of BJT. Now let me show to you

the transistor action how we can achieve a high gain or a high amplification in this case that will be the main focus of our topic in this case.

So let me explain to you how this first topic which is basically NPN transistor in forward active configuration or bias.

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As I discussed with you in the previous turn in active mode of operation, right base emitter junction base emitter junction is always forward biased and the base collector junction is always reverse biased. You have to ensure this base collector junction should be forward biased. Now, one important point which you should note down as far as designing of a BJT is concerned. If you remember the previous talk that the I_S value the saturation current value was depending upon the cross-sectional area of the emitter.

So if you have got two transistors both NPN or both PNP of exactly the same doping concentration but one having a large emitter area as compared to the first case then the second will have a larger current also as compared to the first case so this was one of the techniques by which people use to increase the level of current in a structurally reconfiguring our NPN or a PNP transistor, right.

Similarly you should also be careful the first point which is to be noted is that your base emitter junction should be forward biased which primarily means that your emitter base junction of an NPN silicon transistor should be at least the forward bias should be at least more at 0.7 volts, right for a silicon. And the reverse bias should be much larger than the forward biased please understand this point also. So you have to be very cautious about two

things that is V_{BE} base to emitter junction should be at least greater than 0.7 so the requirement therefore is that V_{BE} should be much greater than 0.7 volts greater than equal to.

And V_{CB} collector to base should be much larger than V_{BE}. So the reverse bias is typically very large as compared to the forward bias itself and that you should be carefully looking into that properly. So now let us go to the second point therefore the electrons from the emitter are injected across the base emitter junction into the base and thereby creating an excess minority current carrier concentration in the base.

We have already discussed this point earlier and we also saw that that the minority carrier concentration will be falling linearly between the emitter base and the collector base junction. As you can see therefore the electron concentration at the edge of that junction is approximately which junction collector base junction is approximately equal to 0 we have also seen this to be true right. Now to ensure that that the minimum number of electrons gets recombined in the base region, right, the width of the base region should be very small as compared to the total length of the dimension of the device.

I will explain to you what does it mean and I will explain this term in a much more detail manner. It says that that the width of the neutral base region neutral base region why? Because you see you had initially P type for an NPN transistor you should have P type now you have minority current carrier concentration N inserting into it trying to make it neutral. The base width W this width of the neutral base region must be very small as compared to this minority carrier diffusion length.

What is a minority carrier diffusion length we define diffusion length as the distance at which because of recombination the value of the minority current or the charge carriers $1/e^{th}$ of its maximum value. So if you entered at this stage and you went to a distance of 1 centimetre and you saw that there was a drop in the number of charge carriers by virtue of recombination. And we saw that $1/e^{th}$ of the charge has actually $1/e^{th}$, so $1/e^{th}$ of the charge has actually fallen down then we define that length to be diffusion length.

So if your width base width is even smaller than that then by the time the electron starts moving I would expect to see that no large diffusion has taken place or no large recombination has taken place sorry. So what we will expect to see therefore is that try to keep the width of the base much smaller than the active diffusion length of the minority current carrier's right and that is what this will minimise your recombination effect. Then the

obvious question asked is that why should we have the recombination in the first place. Well the reason for that is then then we have a control, we have a current controlled device here by controlling the base current I can control the collector current, right. Because I_E is equal to $I_B + I_C$ and therefore if I want to reduce my I_C I need to increase my I_B large make it large.

And as a result effectively V_{BE} controls the value of I_C by making the I_B value vary from point to point or from value to value right and that is what one should be looking into in a detail manner. Let us look at therefore NPN transistor in the forward active mode configuration.

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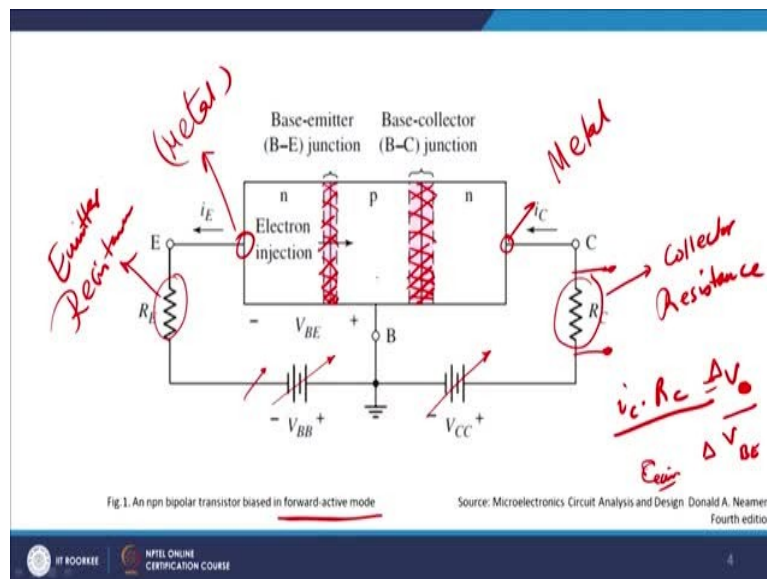
And we define this and we generally therefore put arrow head here and arrow head here assuming means implying that these are variable power sources or variable power supply which is there with you. This R_E and R_C are basically the resistances this takes care of the Schottky resistance at the contact because the contact with this side and this side will have metal contact right we had discussed this point earlier also. This will be metal this will be metal also so both are metal.

So metal contact will have some resistances plus the wire will have some resistances plus any resistance which you want to put it in the external world in order to restrict the current or get a voltage output you put those resistance. You add up all those things and we get a collector resistance here, collector resistance here and we also get emitter resistance here, right. Now what will happen is once this current flows here and I_C multiplied by R_C that is the voltage drop across this R_C that is the output voltage V_O, right and you will be giving a small voltage here input voltage is V_{BE} so output voltage by ∂V_{BE} ∂V_0 will be a gain for a transistor. So this

is a very simple basic form of a transistor as an amplifier. As long as you are able to sustain large current across the collector end that multiplied by the collector resistance will give you a large voltage drop. This voltage drop will therefore change depending upon the value of V_{BE}.

So V_{BE} is therefore your input voltage and therefore output voltage by input voltage will give you the current. If you can see very clearly your base emitter junction this pink side is basically my depletion this one is a depletion width is very small because it is forward biased and it is relatively large in dimension because it is reverse biased, right. And therefore base collector junction will have larger width and therefore larger effective bias whereas emitter base junction will have a relatively lower depletion width therefore a large current will be flowing from the base and emitter junction. Now at this stage what we have not done or what we have understood therefore is two important points I should take care here before we move forward is one is what is known as base width modulation effect.

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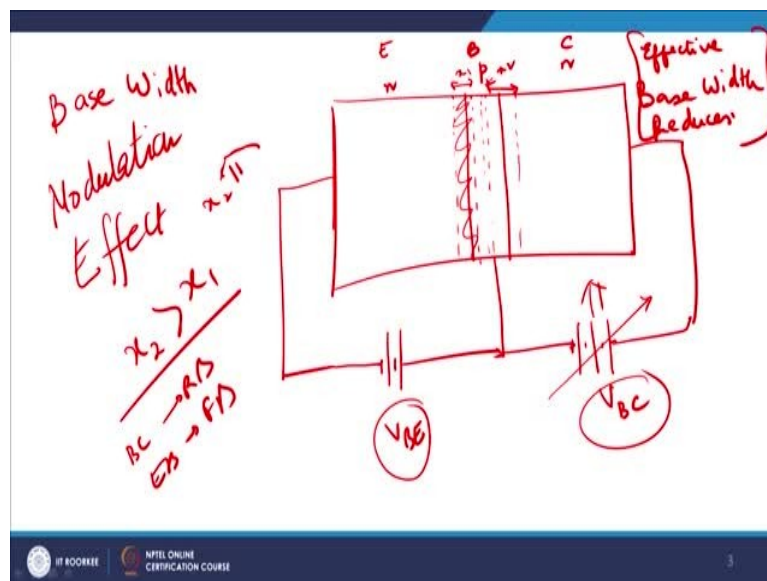
So this is known as and I had explained to you what is known as base width modulation effect again a second order effect in a BJT. If you have a base which is something like this , right then if you look very carefully if it is a forward active mode I am assuming this to be as NPN and this is emitter, base, collector then we bias it such that this emitter base junction to be forward biased and this base collector junction to be as a reverse biased so this is reverse biased. So I defined let it suppose V_{BC} and V_{BE}.

Now you see because of V_{BE} there will be a thin depletion region here but since it is forward biased it will be very thin in nature dimensions. Whereas because of V_{BC} I will expect to see a larger depletion width here. Fine is it okay? So I will see a larger so if this is say X_1 right and this X_2 then obviously X_2 will be larger than X_1 because this is reverse biasing because your base collector is reversed biased and your emitter base is basically forward biased fine.

With this knowledge let us do one thing let us fix up V_{BE}, right and increase the value of V_{BC} we go on increasing the value of V_{BC}, as you go on increasing the value of V_{BC} what will happen? That this depletion width will go on increasing because you know very well that in a PN junction diode or in a simple PN junction if we increase the reverse bias the depletion width becomes larger and larger. So what will happen is the depletion width will become larger and larger, right.

So X_2 will become still further more and more, when X_2 becomes more and more you could easily appreciate that the effective base width reduces, effective base width reduces fine. As it reduces now you allow a larger amount of current to flow through it because now the number of minority current carrier's there or the number of holes there is still smaller. Is this concept clear therefore? I will explain once again what I was trying to say because this concept will be important to understand why the collector current is not behaving as an ideal current source.

What will happen therefore is that as you increase the value of V_{BC} base to collector voltage since it is a reverse biased base to collector voltage as you make the base to collector voltage go higher and higher, the depletion width on the base to collector region the depletion width will also increase as a result what will happen is that the depletion width on the base to collector junction will eat away into the active area of the base.

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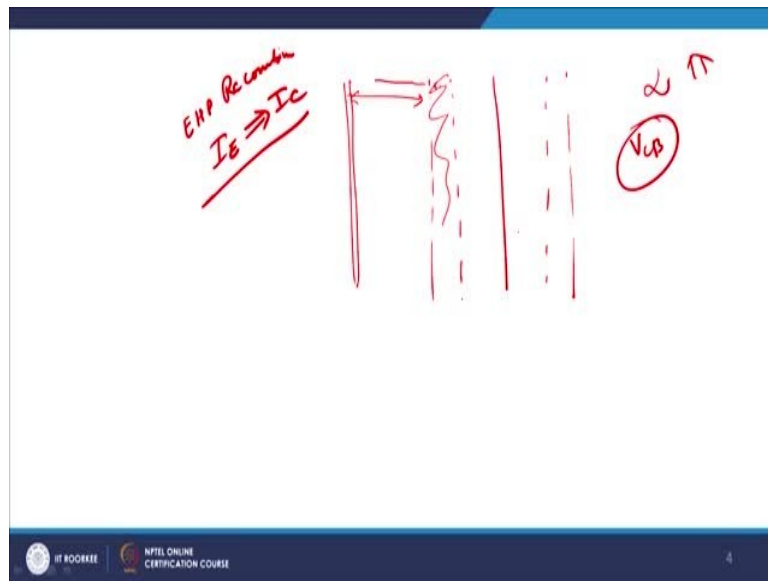
So your base was something like this now initially your collector base junction was reverse biased like this. Now increase the bias and this has shifted this line has shifted to this part and it has become something like this and this is something like this. So which means that this much amount of base is gone therefore and the effective base width is reduced to this much amount only, right.

As a result the EHP electron hole pair recombination will also be reduced right and more of I_E will be allowed to go to I_C. And therefore your α value will increase and as a result the current will not remain constant but current will change with respect to V_{CB}. Please understand this point very carefully. Till now we were all explaining that as V_{CB} becomes larger and larger or as V_{CB} is increasing as long as it is reverse biased collector base junction is reverse biased independent of its value the current will always remain constant and what we were therefore doing was that we were actually assuming therefore it is behaving like a constant current source. The collector is behaving as a constant current source and if you remember the last talk last part you will see that we had removed the collector and replaced it by constant current source, right. I_C was equal to α times I_E and we have shown that this is the constant current source.

But in reality you will see that that depending on the value of V_{CB}, I_C will change so higher the value of V_{CB} I would expect to see a higher change. Not because of the large electric field but because of our reduction in the effective base width which effectively means recombination of electron hole pair will be minimised and therefore more of emitter current

will reach towards the collector side and at the collector side they will register a current, right.

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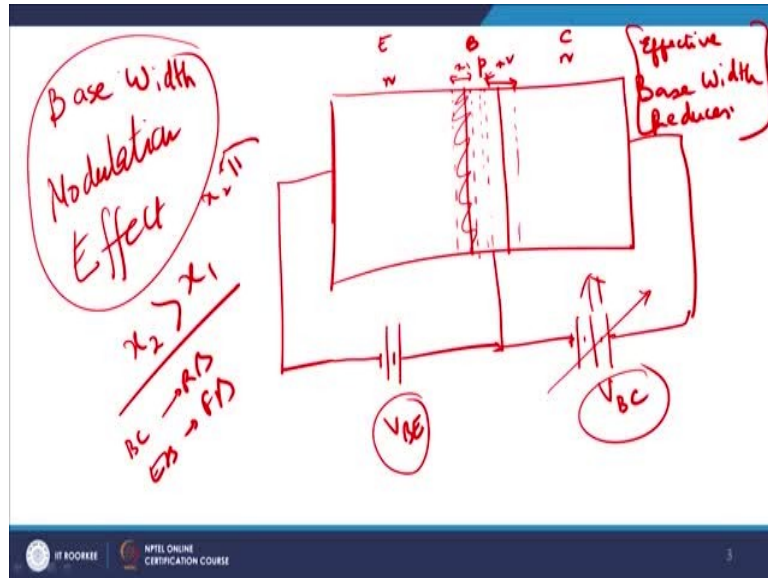
And that is what is known as is also known as Base width modulation effect, right. So we do a small change in our understanding and say that no in second order effect if base width is very very small and we are varying our V_{CB} to a larger extent we would expect to see a larger change in the effective base width which will result in the large change in the output current, right. So this is what we have learned and we have understood as far as this course is concerned.
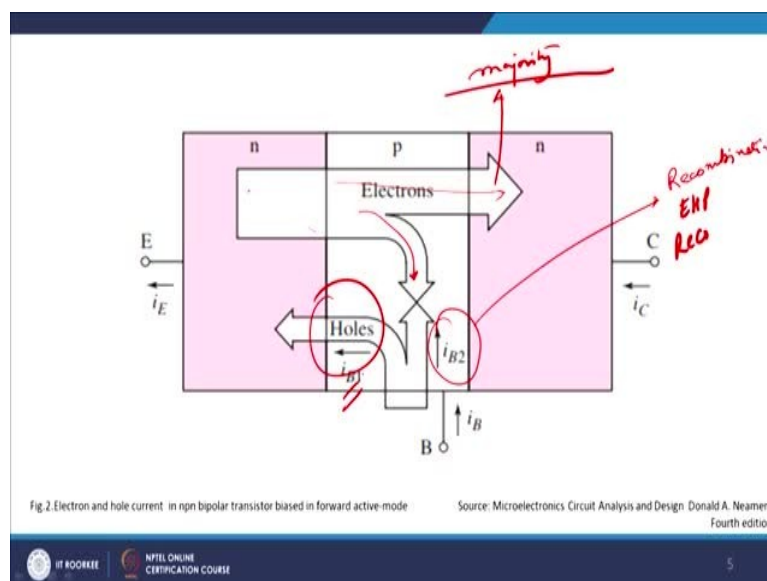
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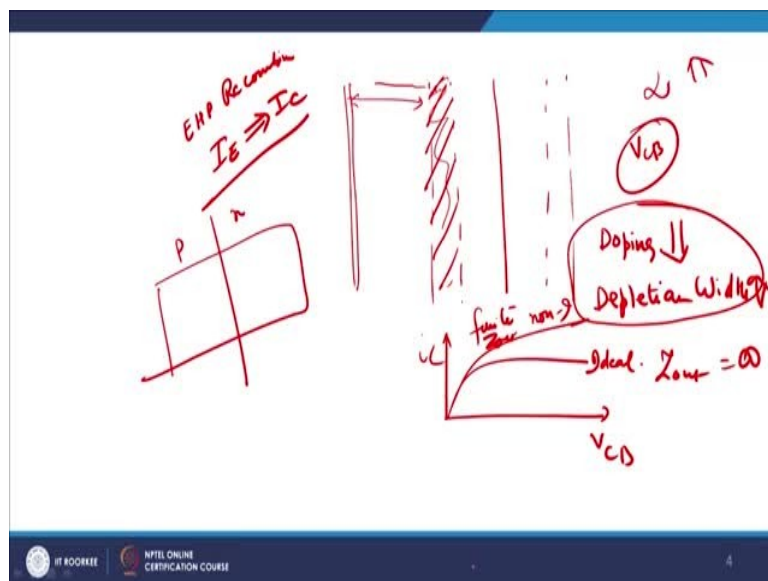
One more thing which I wanted to point out and may be of interest to most of you is that if you remember that if I have a P and N, right and if my doping concentration is low then the depletion width is large on that side so just keep this in mind that if the doping is low right and you apply a bias in a PN junction then the depletion width depletion width will be larger in that semiconductor in which the doping is low fine. So please be careful that the lower the doping more will be the depletion width.

So you see this also adds to the effective base width modulation effect why? Because intrinsically we have discussed the point that the base will have a much-much lower doping right so it is very-very low doped. When it is very-very low doped you automatically end up a larger depletion width on the base side, right. So the variation on the base side will be much larger as compared to the collector side and as a result your emitter base junction or the effective base width will be further minimised in the case of this one, right. As a result you will have increase in current. So if you plot collector current versus V_{CB} ideally I should get something like this but if you see it will be something like this.

So this is the ideal current source whereas this is the non-ideal current source, right. Therefore this will have Z_{out} equals to infinity but this will have finite Z_{out}, Z_{out} is the impedance output impedance. So current source ideal current source will have infinite output impedance whereas a non-ideal current source will have a relatively lower infinite current source. So coming back to the therefore the basic issue once again we saw that for active base emitter is forward and the base collector was reverse biased.
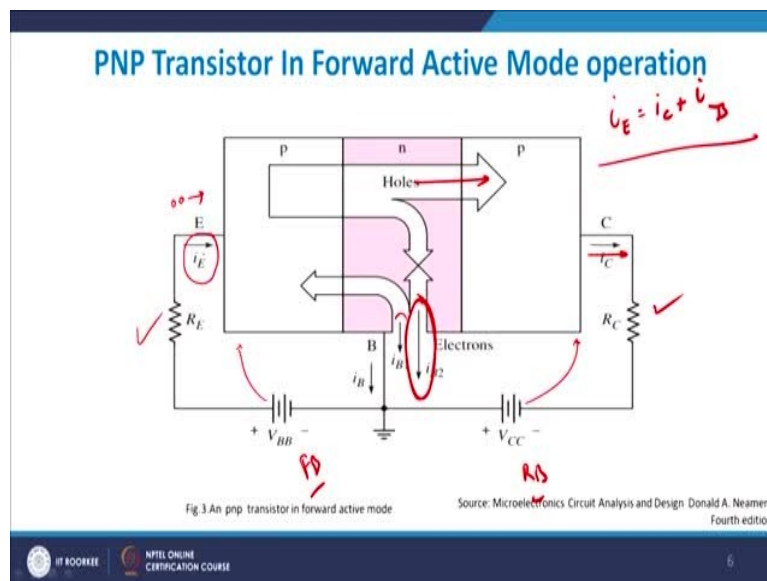
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Fig.2.Electron and hole current in npn bipolar transistor biased in forward active-mode   Source: Microelectronics Circuit Analysis and Design Donald A. Neamen, Fourth edition

We again came back to the same position that if you have an NPN here this is basically the thicker arrow thicker arrow is basically my majority. So majority current carriers are inserted very fast and you get a large amount of electrons coming here, this is what is known as the recombination. So I_{B2} is basically because of recombination between electron-hole so this is basically my recombination current right which is because of electron-hole pair getting recombined and therefore the current which is flowing is basically I_{B2} because of that and please also understand that since this is forward biased holes can easily punch through this emitter base junction this one and will result in some current I_{B1}.

So there are two phases of current I_{B1} and I_{B2}, I_{B1} is primarily because of holes and I_{B2} is primarily because of recombination of electron hole pair in the base region. We understood this point earlier also and we have also got the principle current. Let us see how we can look into we have look at the NPN, can we look into PNP as well which is basically a NPN and PNP in active forward active mode.
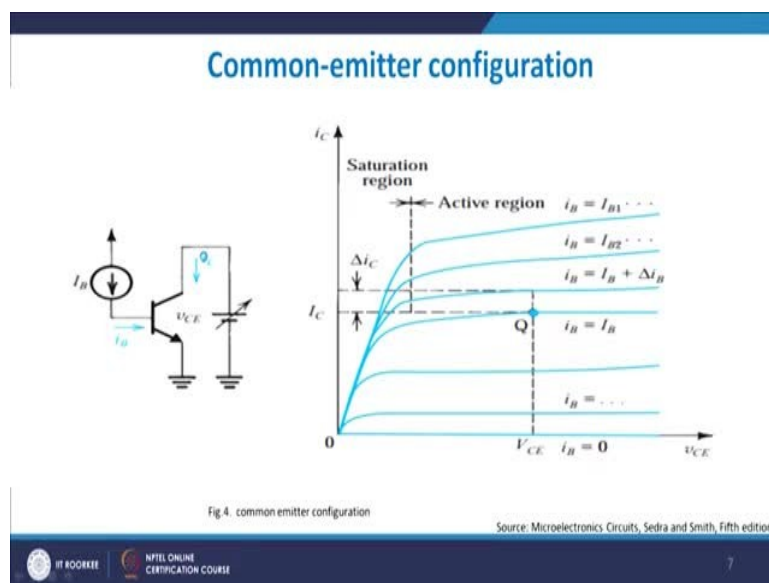
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Fig. 3 An pnp transistor in forward active mode

Source: Microelectronics Circuit Analysis and Design Donald A. Neamen, Fourth edition

The same concept as in the previous case the only thing is the polarity of the battery will now be changed or reversed and you will have V_{BB} in which the positive end is connected to P type and V_{CC} the negative end is connected to P type. So this will be reversed bias and this will be forward biased so we are keeping the same concept exactly the same as in the previous case and trying to formulate a policy for finding out the current.
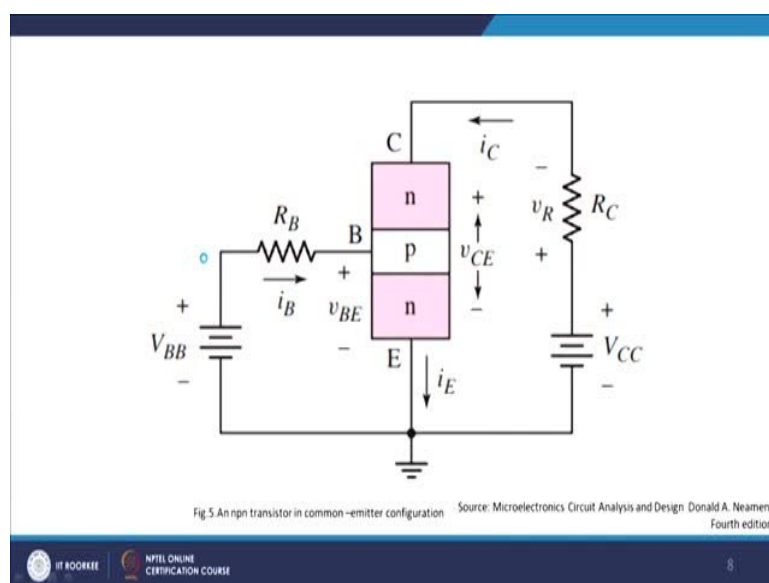
Here also I_E will be equals to $I_C + I_B$ and this will be the only thing is because hole current is basically the conventional current therefore we see that the direction of the arrow head

actually shows me the direction of the holes flow of the holes. So this arrow head which you see here the arrow head which you see here this one is basically the direction of the hole, right. And therefore this shows the holes will be moving in this direction as a result the holes so holes and electrons will combine here electrons and holes will be combined to recruit that many number of electrons, electrons will be moving in this direction so holes will be coming out in this direction so you see I_{B2} to be that electron and the rest of the electrons holes move in this direction and therefore I_C is always in the outward direction. So I_E is equal to $I_B + I_C$, R_C R_B are the resistances which you see in a typical operation.

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Fig.4. common emitter configuration

Source: Microelectronics Circuits, Sedra and Smith, Fifth edition

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Fig.5.An npn transistor in common –emitter configuration

Source: Microelectronics Circuit Analysis and Design Donald A. Neamen, Fourth edition

Now, let me explain to you maybe, just a minute, I will explain to you the common emitter configuration of the BJT because we will now enter into so now we will be seeing maybe in next two lectures or one lecture is that given therefore a transistor can we find out the current flowing through any of the nodes of a transistor provided we know the bias given to that particular node, right.

So what we do, we give a particular set of bias to the transistor any bias by giving forward or negative bias that means can we therefore take a transistor fit into all the four modes available to us and checkout how the currents will flow with respect to the variations in the biases in those transistors. So that we will learn in the next three to four slides in our understanding of this basic concept here.

We will be also one by one as we move along we will deal one by one in a detailed manner and we will see how it works as an inverter and all those things. Before we move forward therefore let me give you a very simple brief understanding of a BJT as an inverter.

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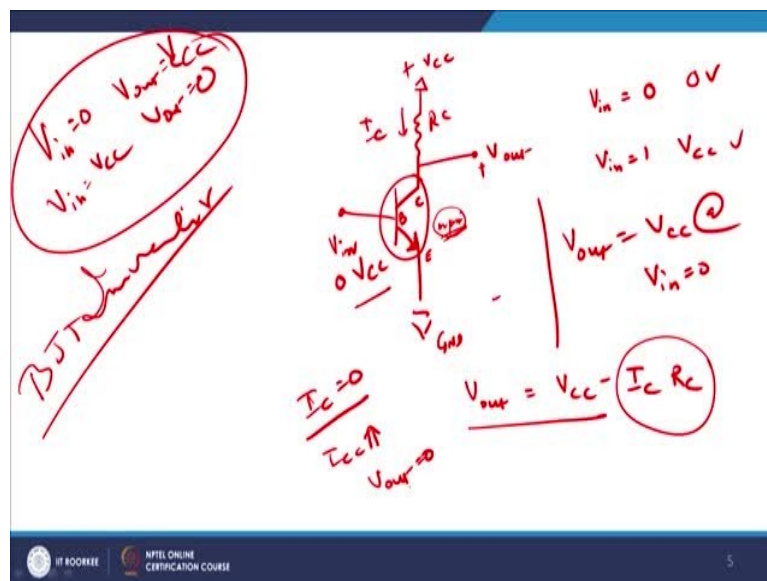
That means if I have got a BJT here, a bipolar transistor, right and I apply a bias here and this is my V_{CC} and this is my ground this is R_C here and I take the output from here V_{out} and V_{out} to ground I take the output so this is positive negative and this is my input I give here. And this is my base and this is basically if you look at the arrowhead since arrow is pointing from base to base to so this is my emitter if you look very carefully this is my emitter, base, collector.

I am only doing it for the first time I will not be doing it again as we move along but just for your information say for the first time base to emitter the arrowhead is looking which means that the direction of the holes are in this direction which means the electrons are moving from emitter to base and therefore this is basically an NPN transistor right this is an NPN transistor which you see NPN transistor that is there with me.

And input side is always on the base side so you see most practically almost 60-70 percent of the case or 80 percent of the cases you give the signal or you give the input to the base side only, right. And try to take the output either from the collector or from the emitter in this case we are taking from the collector and let us see how it works out we will see one by one as you move along. Let us do one thing therefore that let me keep my V_{in} to be so let us look at the digital part of it.

So if my V_{in} is 0 or my V in is 1, 1 means let us suppose V_{CC} or large value and 0 means 0 voltage fine this is the condition which I am maintaining. Now when my V in is equals to 0 then my base emitter junction is cut-off right and therefore no current is flowing no I_E is flowing and therefore no current will be flowing through the circuitry and my V_{out} will be therefore equals to V_{CC} at when at V_{in} is equal to 0 so when my V_{in} is equal to 0 my V_{out} equals to V_{CC}.

Now let me take V_{in} equals to a very high value let me switch it ON which makes it which is transistor is ON this transistor when it becomes ON this potential will go to ground and therefore when my V_{in} equals to V_{CC} my V_{out} equals to 0. And therefore this is how inverter BJT inverter is designed. Very simple straight forward from very first principles of circuit theory. We can predict the value of the output voltage with respect to the input voltage which you see and very straight forward way of looking at it. Also if you want the mathematical derivation I can write V_{out} to be equals to $V_{CC} - I_C$ into R_C, I_C is the current flowing through this domain I_C into R_C. Now if I_C equals to 0 right I get V_{out} equals to V_{CC} and if your I_C is very-very large quantity then this will be very as close to V_{CC} and therefore my V_{out} will be equals to 0 fine.

And therefore I can safely say that depending on the value of the collector current my structure my device which is NPN transistor can be switched on or off. So basic switch nothing very extraordinary difficult. Simply a basic switch which will switch from on state to off state and vice versa as I shown it here in this diagram. In the next class what we have learned therefore is the common BJT in a forward and reverse mode we have also looked into

the concept of base width modulation effect and we also looked into BJT as an inverter we will go into details if required in the later stages.

And in the next lecture we will be looking into BJT common emitter configuration working principles. With that we finish this lecture thank you very much!