Microelectronics: Devices to Circuits
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Lecture 06
BJT as an Amplifier, Small Circuit Model-I

Hello everybody and welcome to the online certification course on Microelectronics Devices and Circuits. Now in this lecture module we will be actually looking into the BJT as an amplifier and then we will also be looking at BJT from small signal model point of view. Let me recapitulate what we did in our previous lectures. We had looked into bipolar transistor, the structure of that both NPN and PNP.

What are the relative doping concentrations of the emitter base and collector and what should be the size of each of the regions of the BJT for the most optimized functioning of the BJT? We have also seen the various electrical characteristics of the BJT and we have tried to ascertain the factor that how can you bias 'C' or emitter base and base collector junction. And we have seen that depending on that there are four modes of operation.

So I can use BJT in analog domain for the purpose of amplification when you are actually biasing it in the forward active mode, right? You can also make it into cut-off provided both your emitter base and base collector junctions are reverse biased, right? So you learn two things, very important things in our by the previous discussion which we had.

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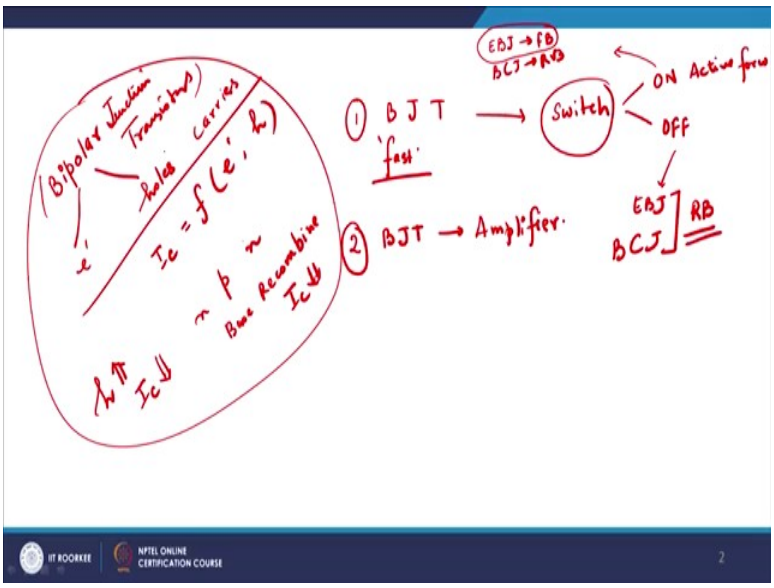

And these two things, the first thing is that BJT can be used as a, of course as a switch, right? So we can go from ON to OFF state, right? How can we go from ON to OFF state? This is again active forward, right? Active forward state, so what will happen in this state? Your EBJ emitter based junction will be forward biased and base collector junction will be always reverse biased, right? So you have here ON state, what is the OFF state? Both EBJ emitter based junction and base collector junction both will be reverse biased in that case it will be off state, right?

So I can use BJT as a switch for sure and therefore whenever we require a heavy switching action BJT can be used and it is a very fast switch, understand it to be very fast. The only problem with BJT switch is that when you go from on to off state and you want to change the biasing, we actually have to change the biasing of the EBJ, from EBJ from FB to RB so EBJ has to be changed.

And therefore we have to be very cautious that how fast this change is. The more fast this change is more higher frequency, at a much higher frequency the switching can occur, right? So that is what we need to look into. We have also learned second thing is that since BJT is able to convert small currents into large currents it can be also used as an amplifier, right? We have seen that in our previous discussion.

So two things are clear at this stage that a bipolar transistor can be used as a switch as well as an amplifier. One thing which we have left in our previous discussion is the name bipolar, why is it known as a bipolar junction transistor? And the reason is very simple because in both NPN and PNP we use both electrons as well as holes for as carriers, right? They use both electrons and holes.

So both electron and hole current is responsible for the total collector current. So the total collective current which you see is actually a function of the number of electrons as well as number of holes. Why number of holes in an NPN transistor? For example, why number of holes? Because if the number of electrons are high of course your emitter current will be high but if your number of holes are also high then the probability of recombination in the base region, right? Recombination will also be high, right? And as a result your collector current will be smaller now, which means that if your hole concentration is larger, large as compared to the previous case I would expect to see my collector current to slightly drop-down as compared to the previous case. And therefore bipolar technology or bipolar transistor as the name suggests will have contribution from both the carriers, electrons as well as holes, right?

And therefore we define that to be as a bipolar junction transistor and that was the name which was given to it way back in 50s when it was actually found out, right? Fine. So we have understood the origin of BJT, we have also understood that BJT can be working as a switch. We have understood the working principles of an NPN and PNP transistor. We have also understood the biasing criteria for the BJT to work fine.

So let us now therefore switch our attention to BJT as an amplifier that is the first thing which we will be learning. So let us just have an outline of the talk which we will be going through in this series of lectures. We will be looking at BJT as an amplifier first of all, so I can, so given a small signal.

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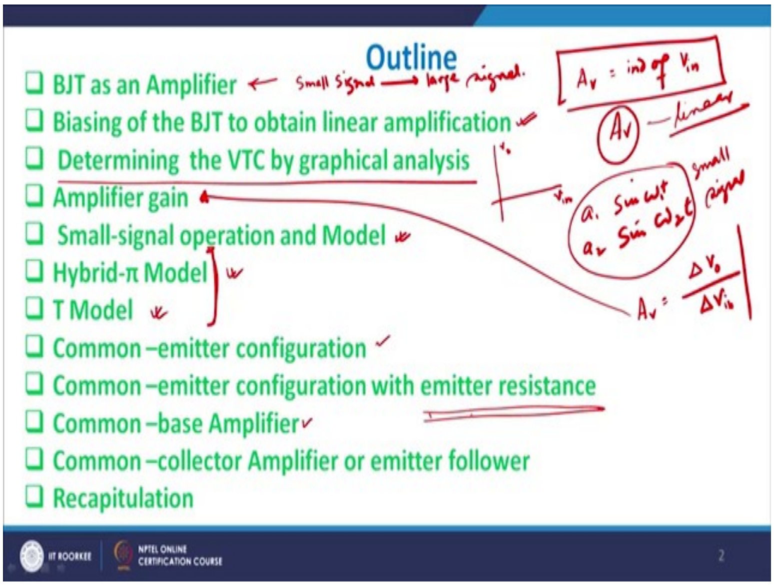

Given a small signal peak-to-peak how can I increase it to a large signal, right? So that is what we will be learning in this lecture that given a peak-to-peak small should I get a BJT as an amplifier? I can get a large this thing. And we are also looking therefore about the biasing criteria of the BJT, right? Because this is quite important, very-very important section.

And the reason is you can have amplification at any one point of time but ideally your amplification should be independent. A voltage amplification should be actually independent of the input voltage, right? So where you bias your input voltage or where is your input voltage should not determine the value of your voltage gain (A_v) right? So please be careful. So therefore if the BJT has to be used ideally as an amplifier then it does not matter to me perse that whether you are giving a signal A_1 *Sin (wt)* or you are giving a signal A_2 *Sin (w2t)* and so on and so forth.

As long as these signals are small signals, right? And we will see that later on I would expect to see that I would get almost a linear amplification. Linear amplification primarily means that there is a linear profiling between the amplification and the input voltages, right? Now to do that we should therefore learn which is the second case that how will you bias your circuit in a manner, right?

And to obtain a linear amplification, right? Then we will therefore learn that how to therefore determine the voltage transfer characteristics by graphical analysis, right? What is the meaning of voltage transfer characteristics? As we will see it is output voltage on the y-axis and V_{out} and on the input axis, on the x-axis we have V_{in}. So how does V_{out} vs V_{in} vary? Right?

So if you vary V_{in}, how does V_{out} vs V_{in} vary, right? And we therefore need to find out A_v as ∂V_{out} upon ∂V_{in}, right? That is what we get as a voltage gain or the amplifier gain. That is what I was talking about in the fourth part of our lecture that amplifier gain will be discussed and on what factors does the amplifier gain depend we will be looking into it. Now in most of the cases these BJT or bipolar transistors as a name does not in the sense works standalone, right?

You have to use this in circuit analysis, so you have to sort of take this BJT and plug it and play it over a circuit for example, right? So what people have done over the years is rather than therefore every time discussing the device behavior if we are able to have a circuit representation of a BJT, right? A circuit representation then every time we encounter a BJT we replace it by its equivalent circuit that is what we will be learning when we discuss Small signal model, Hybrid-π model and T model.

So these are the two models which we will be learning, in these two models we will be able to therefore given any BJT in any configuration 'C', common emitter, common base or common collector I will be able to give you a corresponding circuit model for that which can be plugged and played within any of the BJT configurations for better understanding. We will be again looking into we will be revisiting again the common emitter, right? Common base and common collector amplifier and we will be looking with how does it vary when you have an emitter resistance being applied here, right? So please remember yesterday's talk when we were discussing common emitter, there was no emitter resistance.

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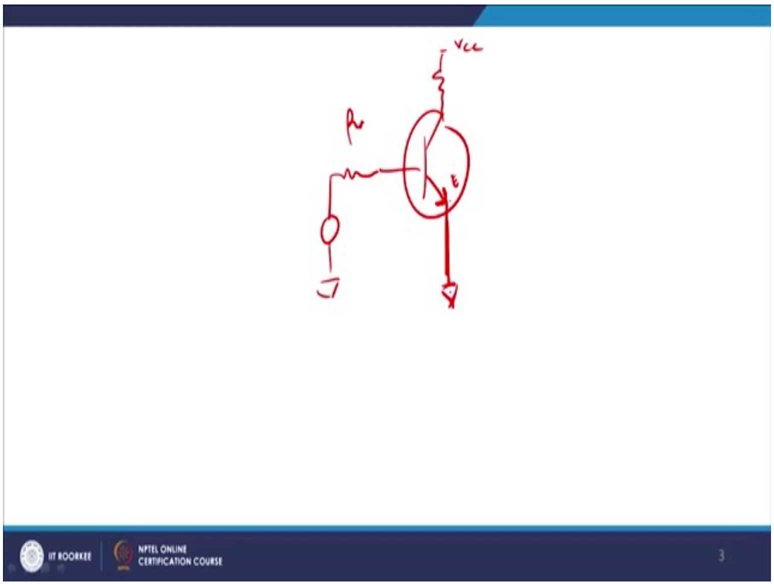

So what we did in our previous turn was that we were something like this that it was grounded, right? And this was R_C and this was V_{cc} and this was R_B, right? And this was applying a base and so on and so forth. So this was my BJT and I... I... my emitter which was this one was totally grounded we did not apply any potential here, right? Or there was no resistance between the ground and the emitter node of the BJT, right?

We will like to see how inserting a particular resistance in the BJT in that particular emitter node, how does it influence the overall capability of the common emitter configuration? So these things we will be watching along as we and then finally we will recapitulate what we studied across this lecture series, right?

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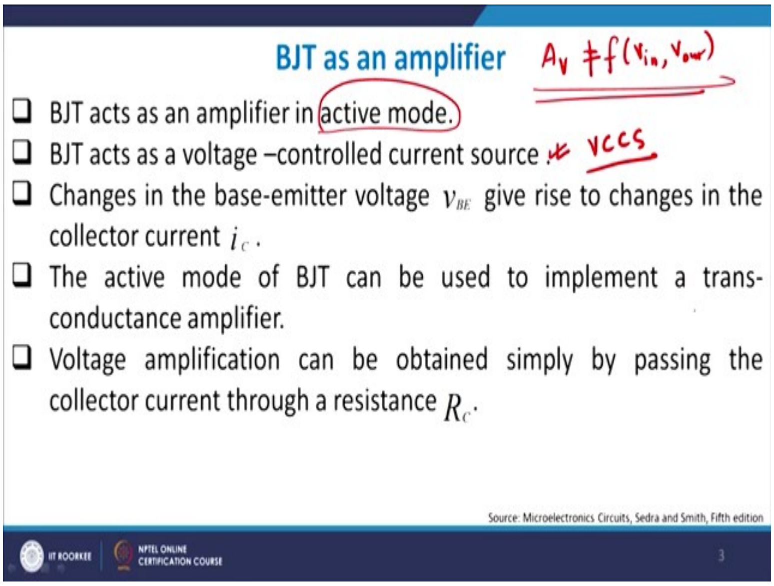

So this is what we will be looking into, the first thing will be that BJT is an amplifier. Well as I discussed with you the BJT will act as an amplifier only in the active mode, right? It will also act as amplifier in other mode but that amplification will not be a linear amplification and therefore my ∂V_{out}, ∂V_{in} which is basically the voltage gain might be a function of V_{in}, right or V_{out}. In a sense that if V_{in} therefore varies my A_v will vary and therefore that is not a good idea.

In reality you should be very careful that voltage gain should not be a function of V_{in} or even V_{out}. It is not a V_{out} but surely not a V_{in}, right? So this criteria has to be held very confirm or in a very careful manner that a voltage gain cannot be should not be a function of V_{in} and V_{out}, right? And that is quite important observation to take care of that typically they should be holding no functionality in terms of V_{in} and V_{out}.

Now as we have seen therefore that BJT therefore acts as a voltage control current source, why? This is basically voltage control current source. So if you remember we have four types of sources.

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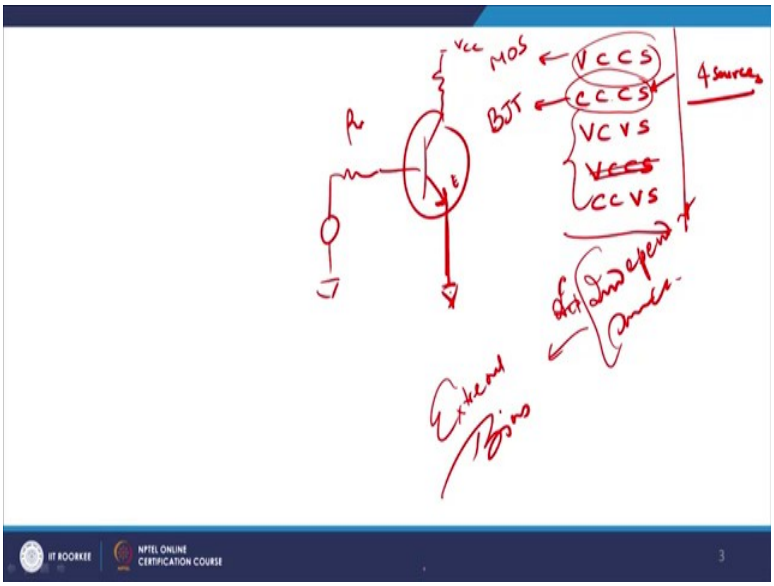

One is known as voltage control current source, current control current source, right you have a voltage control voltage source and you have a current control voltage source, right? So there four types of sources which is generally available to any electronic designer, right? An example of current control current source is basically a BJT right? A MOSFET for example is a voltage control current source, so a MOS device we generally get, think about these to yourselves and you can get it.

One example of BJT is also a voltage control current source just like BJT and we will see that later on but primarily BJT is a current control current source and therefore it is basically a, because the current in the base side of a BJT will determine how much amount of current there is in the collector side. Therefore we define that to be as a CCCS domain as far as BJT is concerned, right?

So these three things you should be very careful that these are four sources, right? And these four sources are all dependent sources sorry independent sources, but each source is having an external bias, right? External bias, so all of the sources are having external bias but they are of independent nature, right? So this is what we will be learning as we move along.

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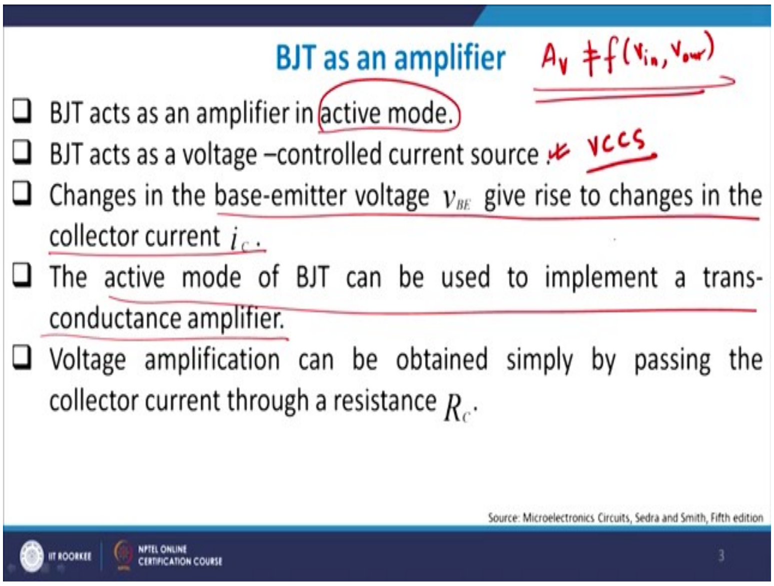

And therefore what we have learned just now therefore is that a change in the base emitter voltage which is this one gives rise to a change in the collector current i_c. I think this has been already discussed to a larger extent so for example if you are using a silicon transistor and your V_{BE} is less than 0.7 you can be amply sure that the emitter base junction is cut-off and therefore there is no current appreciable amount of current flowing through the emitter base junction.

So your device will be in OFF state in that case because you are not allowing any of the transistors to electrons to flow in case of NPN transistor, the majority current carriers you are not allowing it to flow. But once your base emitter voltage exceeds 0.7 in case of silicon which is the cut-in voltage I would expect to see an exponential rise in the current by varying a V_{BE}, right?

So if you vary V_{BE} near the knee point of the PN junction then I would expect to see a large amount of current flowing through the collector side once the input voltage is larger than the cut-in voltage or 0.7 in case of silicon. As I discuss with you therefore the active mode of BJT can be used to implement a trans-conductance amplifier, forget about this word trans-conductance we will be looking into it in a detail manner.

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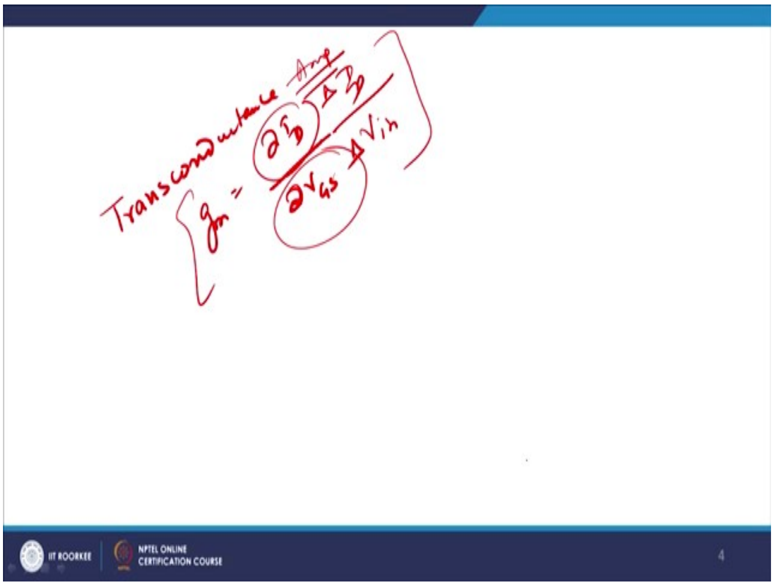

But you know you must be remembering what is transconductance? Transconductance is defined as g_m is defined as ∂I_D, ∂V_{GS}, right? Is ∂I_D, ∂V_{GS} which means that it is basically a rate of change of drain current with the rate of change of gate to source voltage, right? That is what is g_m. Now therefore what is a transconductance amplifier? Transconductance amplifier is an amplifier which amplifies the output current because of the change in the input voltage.

So this is your input voltage, right? So there is a ∂ of V_{in} here because of which there will be a change in the output current ∂I_D and division of that is basically my g_m Transconductance, right? And therefore it is also referred to as a transconductance amplifier. So we refer to this as a transconductance amplifier and that is quite an interesting topic which people have been dealing with when they are dealing with these BJTs or bipolar technology.

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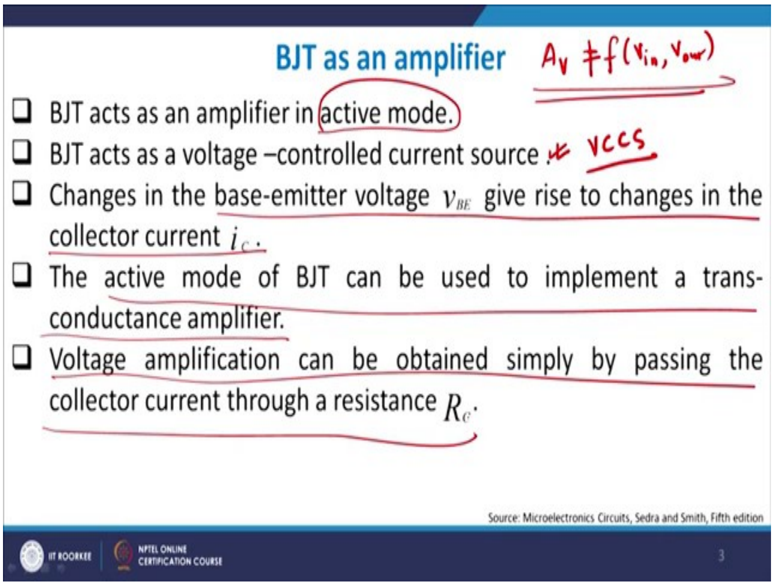

Now therefore so that is what I was saying that, so the last point is that a voltage amplification, right can be obtained simply by passing the collector current through a series resistor (R_c). So you have i_c available with you because of a collector current is available with you. Now if the collector current you are forcing it to pass it through a resistance R_c then i_c R_c is basically the drop of the output voltage, right?

Now even if your input voltage is small and your output voltage is large your A_v will be therefore typically very high of the order of maybe 100, 200, 300, and so on and so forth, right also referred to as a voltage gain in this case. So two things we take away from this slide; BJT should be in active mode if you want it to act as an amplifier, changes in the value of V_{BE} will give rise to a change in the value of i_c.

The third thing is that it is also referred to as a transconductance amplifier because the input is basically a voltage and the output is basically a current and the amplification can be thought of as the output current passing through the resistance R_c. The voltage drop across that resistance is defined as my output voltage, right? And the division of output voltage to input voltage is therefore referred to as a voltage gain, right?

Okay, let me come to the next slide and show to you how biasing of a BJT can be used to obtain a linear amplification, right? And we will see step-by-step each one of them in a much more detail manner.

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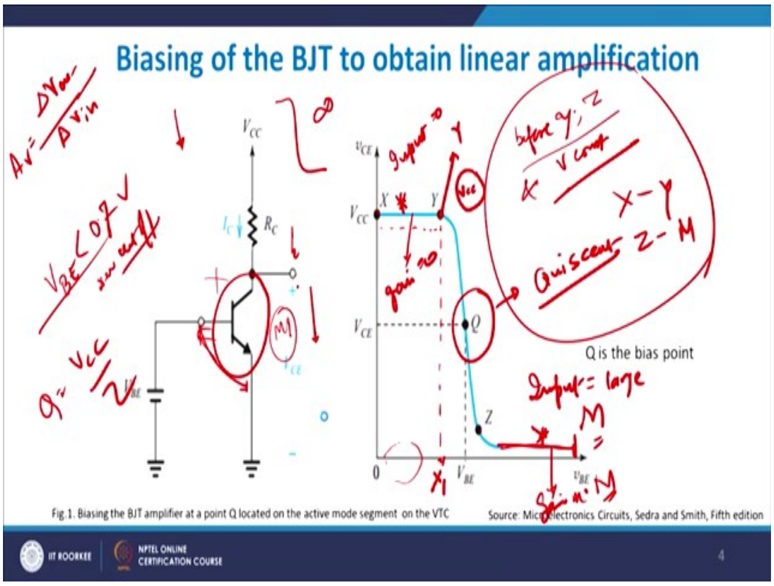

Now if you look at this left hand side figure which is this one, right? I have an NPN transistor which is marked by this red circle let us suppose, right? And what we get is that we bias it by an external source V_{BE} and we have I_c and V_{CE}, right? Now the obvious question how do you physically amplify? When you amplify any signal, how do you do that physically? Well, first of all you apply a DC biased, right?

You apply a DC bias onto the device itself which you are supposed to amplify. Once the DC bias is applied you need to superimpose the small signal model over the DC bias in order to sustain a output voltage variation, right? So I therefore mark my DC level and superimpose with that I have an AC cycle available with me that multiplied by (A_v) Voltage gain gives me the output for any BJT.

Now that we will come later on, let us see, what are the functionalities of linear amplification? Now if you look at this figure here when V_{BE} is less than 0.6 or 0.7 volts which is on this side, somewhere here, right? The device is cut-off, right? The device is cut-off, so when the device is cut-off automatically all the V_{cc} will fall across the output voltage and that is what is happening.

For the output voltage you have got V_{cc} and remains V_{cc} up till a point Y where what is happening? Where you will have the other Institute amplification to be zero in that case. So the amplification will start after a point Y but from the point of view operation we say that till Y or till let us suppose Y on this axis and say X_1 on the V_{BE} scale, right? I can safely assume that the device is in the OFF state and therefore output is at V_{cc}, agreed?

When my therefore voltage crosses 0.7, right? It switches on my transistor here as a result the voltage at this point starts to fall to V_{dd}, sorry at zero bias and then something happens here, right? We define a point which is known as the Q-point or the bias point where you need to sustain or you need to keep your device there in order to ensure that the device is in linear amplification mode and I will explain to you why is it like that.

See if you look very carefully, *Y* and *Z* are the two points at the two extremes after which the voltage V_{CE} is almost independent of V_{BE}, it is a straight line. Before *Y* and after *Z* actually, after *Z*, I have not drawn but after *Z* it will look something like this. So almost a straight line, right? In both the cases before *Y* and *Z*, right? Before *Y* and *Z* we expect to see that the voltage is constant, right?

The voltage is constant and then after *Y*, the output voltage starts to fall down and you know the reason why because after your input voltage has crossed the value of your ON condition this tries to switch off this *M1*. As it tries to switch off this *M1*, more and more current will flow and you will expect to see this to fall down and when the time will come and this goes off or almost very near to zero then this will result in this point which is the starting point to be actually elevated to high-value voltage that is what is happening here.

So as you make your Y_I move slightly higher there is a certain drop in the voltage and the reason is in that case the device is in the on state and therefore when the device is in the on state it pulls all the extra charge carriers towards its center living its neutral charges that did not happen and therefore what will happen is at point *Y*, I would expect to see that the output voltage is latched to V_{CC}. Now if you input an active voltage in fact it is V_{CE} which is latched to a high value of V_{CC}. Now you see we define the Q-point quiescent point, Q is referred to as quiescent point or a point which is highly stable point, right? So these two are the definitions of the Q-point which is seen in front of you. And which means that this Q-point by application of an external bias can move up and down but within the linear regions of amplification process, right?

And that you should be very careful as far as designing is concerned that you cannot let the Q move anywhere it likes but across the only across the small signal domain, right? As such that you get a large amplification in this area. Now if you see very carefully as the voltage exceeds *Z*, right? Input voltage exceeds *Z* that ensures that this device is basically your cut-off, so V_{BE} is very-very large.

Very-very large primarily means that your cut-off has taken place and the voltage actually goes down almost to zero value, right? What is left for you to understand therefore is how does Q-point behave which is this point. This is also referred to as a quiescent point, how does it behave and how does it help us in averting any problem? See if you look very carefully, if your device is biased here or here, you are either in input stage zero, so this is the input stage zero or you have got here input, a large input, fine.

So a large input and a small input I can show it on the same graph and this is how it is done. Before we show you how it is done, we will just comment on the fact that the points between Y and Z, right are so small spaced between each other that they seem to be merged with each other, right? But there are sufficient numbers of points to evaluate beyond Z and Y that this region is highly amplification zone and this region are the basically a digital zone.

So if you want to work in digital electronics or digital domain you need to work in the region X, Y, and Z to this much point say this is M, Z to M, right and so on and so forth, you do not have to go for all the details which is available in the literature, open literature for this case then. Now typical value of Q is such that, Q is somewhere around V_{CC} by 2, right? So whatever is the input voltage or V_{dd}, I am using or whatever clock voltage I just have to half it whether we talk about quiescent characteristics or a low-power characteristics.

Now what will happen is that as you... as you... for example V_{CE} is equal to Q-point as you can see and the X-axis is V_{BE}, right? Now let me say that therefore if you want to work in digital domain X, Y and Z, M are the most logical digital principles because it is 1, 0 and 0, 1 here. And this slope gives rise to a constant gain, are you able to get the picture? Because A_v will be equals to ∂V_{out} by ∂V_{in}, right?

So it is ∂V_{out} by ∂V_{in} which means that my output voltage will depend upon the input voltage as such, right? Secondly, what about the gain at X, Y and Z, M? Because gain is change in the output voltage upon change in the input voltage. So though your input voltage is changing, output voltage is constant and therefore your gain at this point is exactly equals to gain at this point, right?

Fine, so gains are exactly equal in both the cases, but gain shows a drastic change in the middle region depending upon how steep the slope is. So if your slope is very-very steep, right something like this, you will have even infinity gain shown to you, right? And that is how people work with inverters for starting application purposes, right?

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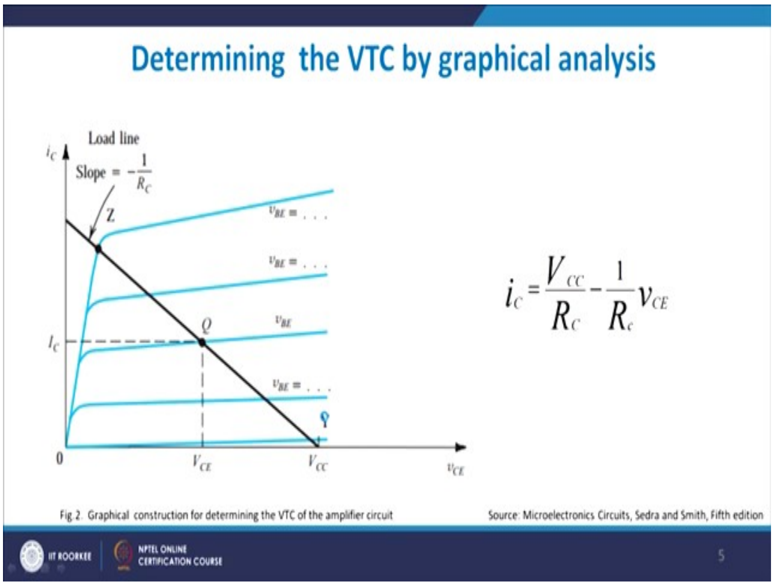

We now therefore come to determining the VTC by graphical method, right? How will you find out the voltage transfer characteristics graphically or looking at a picture at a graphical point of view, right? And that is what is required and I will discuss that in this section in this lecture, right? Let us take one important point, let us take BJT switch or the BJT transistor as an amplifier, right?

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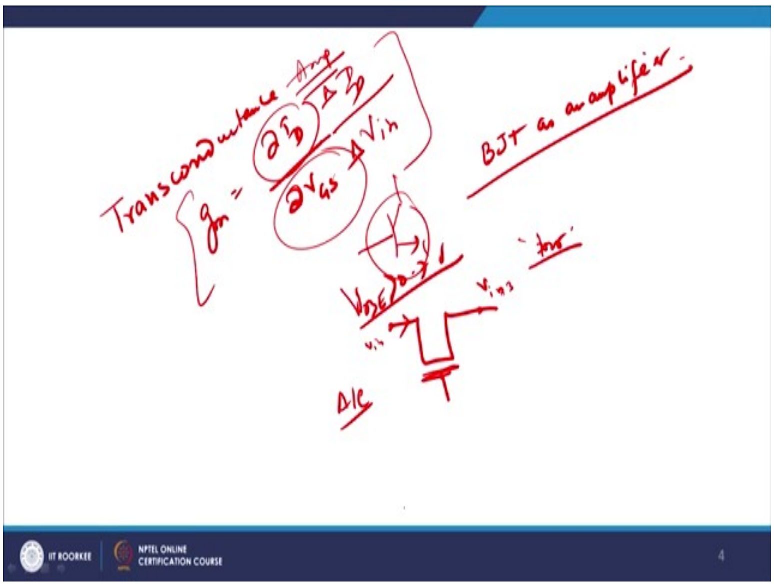

BJT as an amplifier let us take, right? So what we do is, we try to provide the candidate enough database in order to appreciate the working principle. Let us see how it works out. So if I have a diode connected load for that matter any load, right? What I am trying to tell you is that, in this case as you switch on the value of input voltage and one of them maybe AC, you expect to see a large amount of current flowing here but since it is normally on-off state there will be no current flowing through the inverter or in this matter CMOS and therefore you require a person from inside to switch it on, right?

How will you do that? By simply making this BJT work at typically at V_{BE} greater than 0.7 volts. When you make it V_{BE} greater than 0.7 volts you switch on this base emitter junction and as a result output is available to you.

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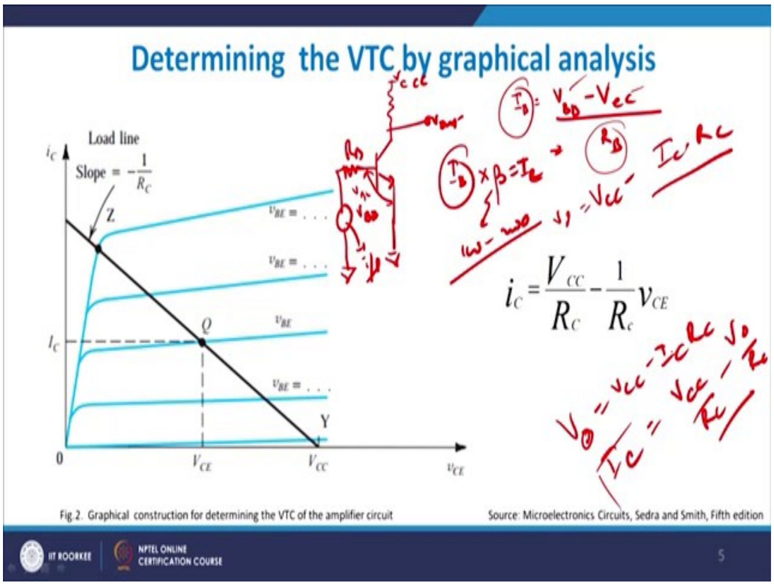

So what was the concept is that in a common emitter mode configuration, let me draw for you the common emitter mode configuration design, right? And this is without the collector emitter configuration V_{cc}, right? You had R_B and then you had V_{BB} and then you had this and then on the emitter side you had this, this is your output and this is your input which is basically a sinusoidal input.

So what has happened is that because of this V_{BB}, I will have a current, this V_{BB} is here, so what will happen is there will be a base current I_B which will be formed by doing V_{BB} minus V_{ec}, so this is the breakdown voltage. So we write down I_B to be equals to this divided by R_B where R_B is the base resistance here, fine. So you put the value of V_{cc}, you put the value of V_{BB}, put the value of R_B and you get I_B, right? You get I_B.

Now once you get I_B you need to multiply that with beta in order to get I_C, right? And this β is with the order of few 100s to 200 value and I get i_c, right? I get i_c here the collector current. Now this collector current multiplied by R_C gives you the voltage drop across the resistance, right? So that is what you get as that so what is output? Output is V_{cc} minus I_C R_C is equals to V_{out}, fine. So I get V_{out} to be equals to V_{cc} minus I_C R_C, right? And I get this quantity here and therefore I get I_C to be equals to V_0, right? So V_{cc} by R_C and I will get minus V_0 by R_C, so I get I_C to be like this, right?

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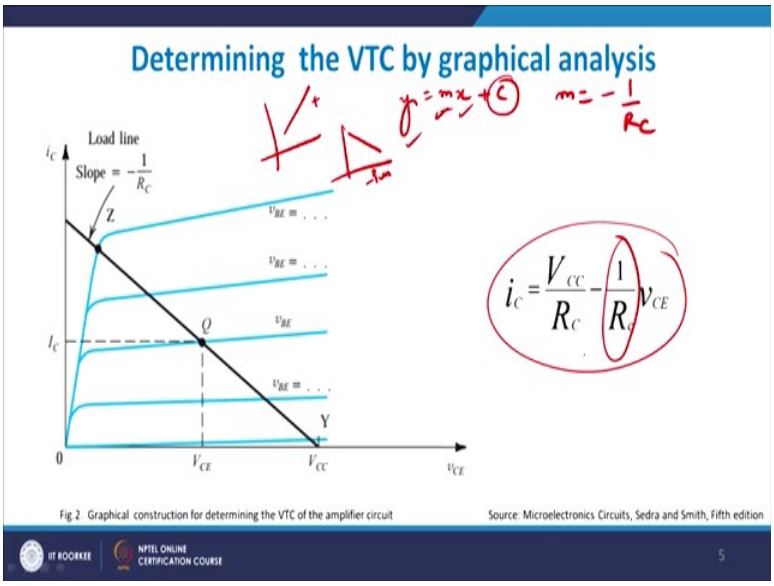

Which means that if you look very carefully or even if you look at this particular point I can safely say that this is the final content that the collector current is only depending on the value of V_{cc} by R_C and it depends upon minus 1 by R_C V_C which means that if you compare with the fact Y equals to m_x plus c, m is basically your 1 by R_C, right? So why with the negative sign because the slope is negative, right?

So if I have something like this, this positive slope, if I have something like this it is a negative slope. Since this line is something like this in the reverse direction you get a negative slope and therefore m is fixed at minus 1 by R_C, right? Now therefore if you know m you know XY, I can get the value of C, right? So this is a standard methodology which people use.

Now what has happened is over the years and typically in the early years we used to find out the VTC or the voltage transfer characteristics by graphical method, fine. So we will do that in the next turn, today we have learned the basic idea of a short-circuit or a small signal model next time we will be learning how to find out the voltage transfer characteristics by graphical analysis, a detailed analysis will be followed, okay. Thank you very much.