Solid State Devices
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Lecture - 32
Bipolar Junction Transistor (Contd…)

We now come to the last lecture of the Bipolar Junction Transistor. Let us see what we achieve in our previous lecture. We explained these common emitter output characteristics and we identified the breakdown and saturation regions and the active region.

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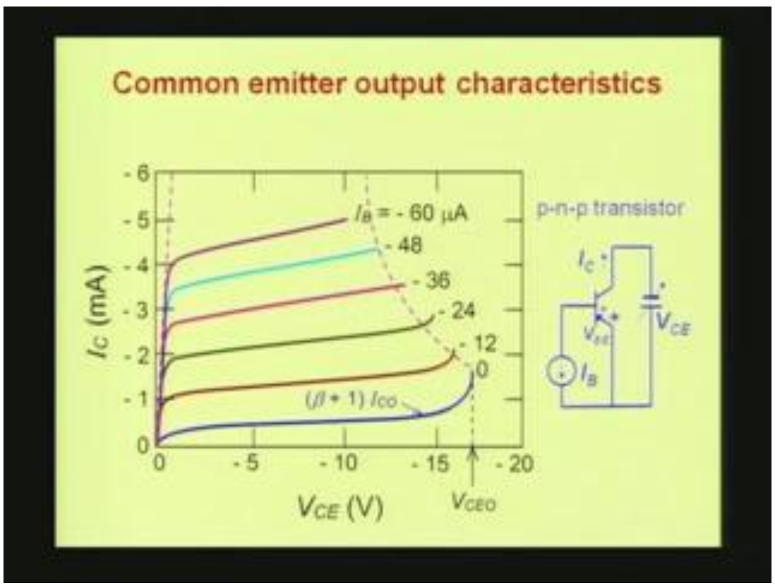

Then we explained the variation of beta with collector current. The beta is small at low collector currents, it increases reaches a peak and then falls. Please note the range of collector currents considered, this is for a small signal device, all the characteristics we discussed in this course are for a small signal device.

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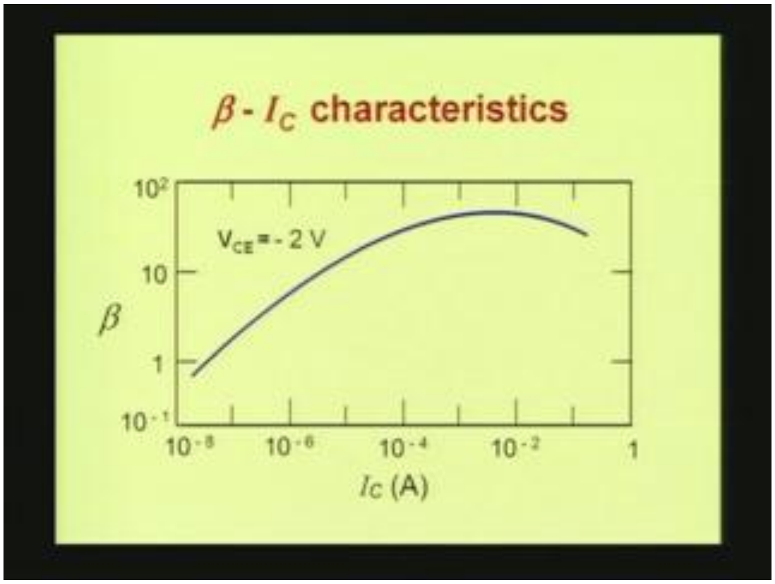

So, the range of the collector current is from 10 to the power minus 8 amperes to 1 ampere here which is a very wide range and that is why the axis is logarithmic. The variation of beta on the other hand can be seen to be from about 1 to a peak of somewhere about 70 to 80 and then there is a fall.

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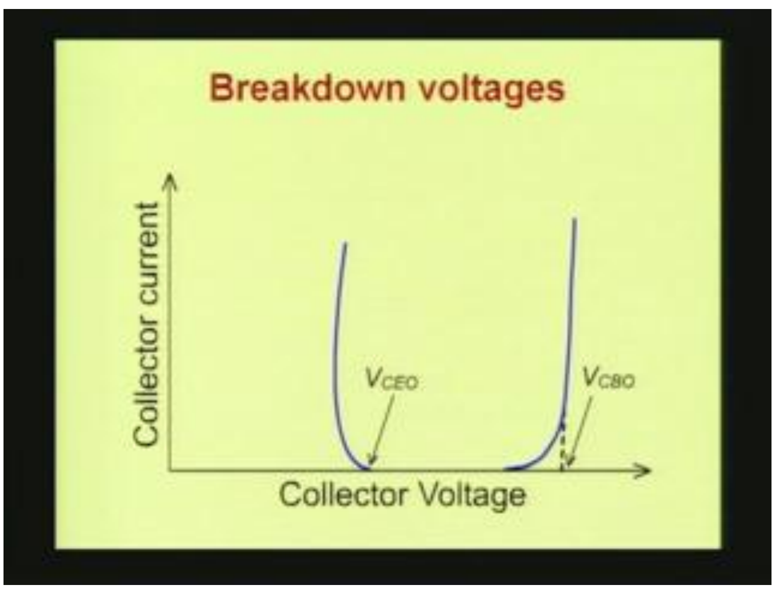

Next we also explained the breakdown voltages. The two important breakdown voltages of a bipolar transistor are the V_{CEO} and the V_{CBO}. Now we will start from here in this lecture. If a student is asked to draw the common emitter characteristics qualitatively for a bipolar transistor how should you go about drawing the characteristics so that all the features are correctly captured? This is the way to approach drawing of common emitter current voltage characteristics.

First we choose the axis I_C and V_{CE}. For a p-n-p transistor the voltages here are negative and the collector current here is negative. For an n-p-n transistor these currents are positive and these voltages are positive. Now what we should do is, we must first identify the saturation and breakdown regions. The saturation region is something like this and this is the breakdown region. Having done this, now, we must test the characteristics noting that the slope of the current versus voltage curves will go on increasing as you move to higher and higher collector currents. It turns out that, if you extend this curve, this is the collector current versus collector voltage curve in the active region. This is saturation and this region is so called active region.

So in the active region if you take this collector current and then you extended backward it will meet somewhere here and interestingly the other curves also will meet almost at the same point. Therefore the way to draw these active region characteristics is to start from this point and draw the other curves. This is the way we have to draw the curves for different values of I_B. Here you have the breakdown. So this curve should actually be shown as it is going up. This is the breakdown, and now we can join these curves here. As we already explain these curves do not exactly start at origin but they start from slightly below the origin. But this difference is very small so one can show when you are showing the voltages in the range of tens of volts and collector current of the order of milliamperes you can assume the characteristics to start from origin.

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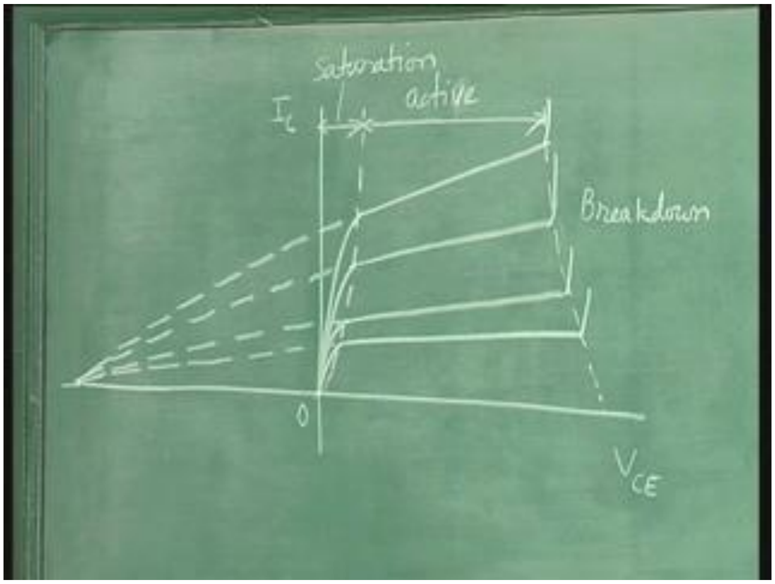

So this is the way one should draw the curves then all the features of this current voltage characteristics will be correctly captured. That is, you will show the curves corresponding to higher and higher base currents to have higher and higher slopes. So we first identify the saturation region then the breakdown region and between the two you have the active region. Then you draw the curves in the active region where all have increasing slope as you move up and all these curves meeting at a point here. Then you complete the picture by drawing the curves in the saturation region. This is the way once should draw the I_C V_{CE} curves.

Another point is what is the importance of the collector to emitter breakdown voltage when the base is open BV_{CEO}? So either BV_{CEO} or simply V_{CEO} that is collector to emitter breakdown voltage when base is open. To understand this let us look at the circuit of a common emitter amplifier. So this is the circuit diagram of a common emitter amplifier. Now, in this circuit supposing because of some fault this particular base terminal becomes open. So, many faults can occur in the circuit. Supposing this is the fault the base terminal becoming open. In that case the entire collector power supply voltage will come across the collector to emitter because when the base is open the current in the collector is very small. Therefore voltage drops across this resistance and this resistance will be small and entire V_{cc} will come across collector to emitter. Therefore if the transistor does not have a good BV_{CEO}, that is if unless BV_{CEO} is greater than V_{cc} the transistor will breakdown. Therefore a large current will flow between collector and ground and the power supply will end up delivering a very large current and there can be problems here. In fact burning out of the circuit can occur or the power supply may trip, these kind of things may happen.

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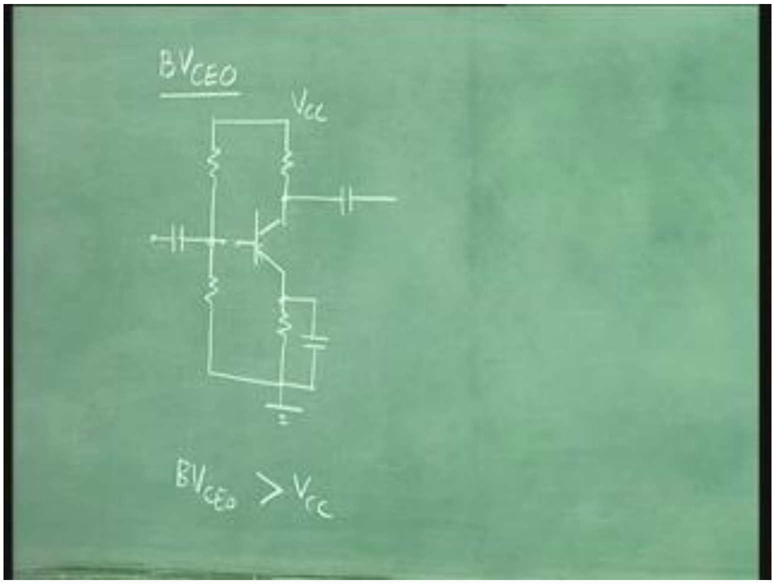

So what you find is, whenever the base terminal is open and because of some faults the entire collector voltage appears across the collector to emitter of the transistor, this is the problem. Therefore in this mode of operation of the circuit the breakdown voltage of the transistor should be higher than the collector power supply that you connect. And that is the significance of this BV_{CEO}. So whenever you choose a transistor for an application you should find out what is the collector power supply you have to use for the particular amplifying application and then you must choose a transistor whose BV_{CEO} is more than the power supply voltage. That completes the discussion of the common emitter output characteristics. Next let us briefly discuss the common emitter input characteristics as shown in this slide. Here you see that we are plotting the base current as a function of emitter to base voltage. This circuit diagram is also shown next to the characteristics. Now what you find is, when you change the collector to emitter voltage your I_B versus V_B curves are very slightly different for different collector to emitter voltages. So, for minus 5 V and minus 10 V the characteristics are slightly different. Now let us understand these curves.

Common Emitter input characteristics:
Since it in a p-n-p transistor both these access are negative. Now this is nothing but a diode like characteristic. So because if you see the slide again this is V_B and this is I_B so the relation between these two will be the same as the current voltage characteristics of this emitter base diode. Therefore you are getting the exponential shape.

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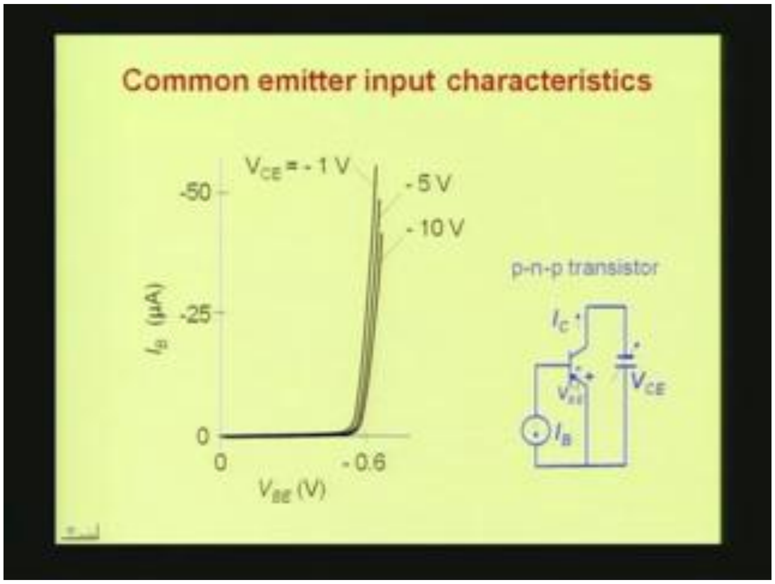

Now what you need to understand is why these curves depend on the collector to emitter voltage. Why is it that if you increase your collector to emitter voltage magnitude your curves are shifting to the right. So this is increasing V_{CE}. For a p-n-p transistor this V_{CE} is negative therefore we put a modulus here. So increasing V_{CE} via the characteristics is slightly different. Now this is because of base width modulation. With the output characteristics we can generate the input characteristics also based on the excess carrier distributions in the emitter base and collector.

So let us draw the excess carrier distribution for different values of V_{CE} assuming the I_B to remain constant. That means we need to explain that if you maintain your I_B constant and when you change your V_{CE} there will be a small change in V_{BE}. And if V_{CE} is more the V_{BE} will tend to increase very slightly. Let us see why this should be so. Now let us draw the excess carrier concentration for one value of collector to emitter voltage. This is the emitter, this is the base and this is the collector.

Now, when you increase your collector to emitter voltage your collector to base voltage will also increase because emitter base voltage is forward bias and there will be a very negligible change in the emitter base voltage because the collector to base voltage will increase the base width is going to shrink because the depletion layer here is going to increase. But you are maintaining your I_B constant so if I_B should remain constant then what will be the carrier distribution for a new collector to emitter voltage. Now you know that the base current in a transistor contributes to the electrons injected into the emitter and it also compensates for the recombination of holes in the base in a p-n-p transistor. So the electrons here which you are providing, a part of these are used here for injection into emitter and other part is used for recombination in the base so this is the flow diagram.

Let me remove this E and B to avoid complication. If I_B should remain constant and your base width has decreased, now how do you maintain the base current constant? So base current is the sum of this current and that current, the recombination current in the base and this. So, the only way you can keep the base current constant is to increase emitter base voltage slightly.

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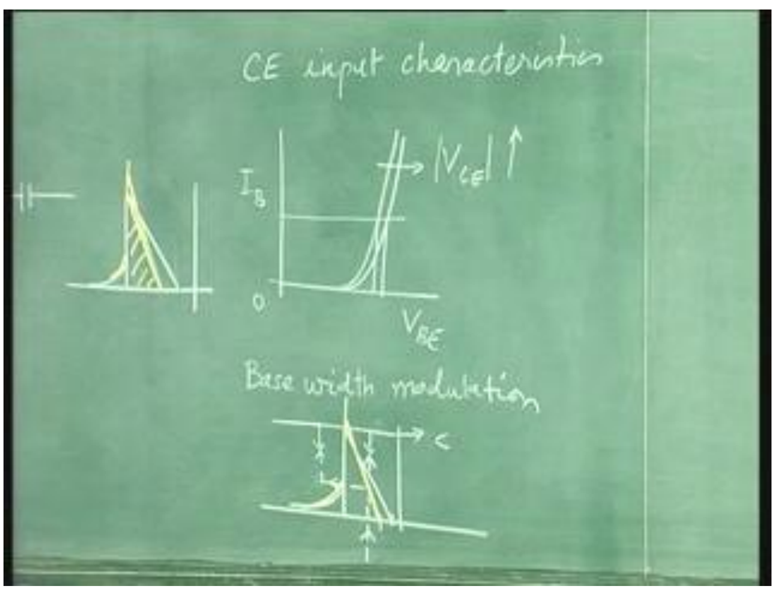

This is your new distribution because if your base emitter voltage would have remained same please note what could have happened. Let us draw the picture again. If emitter base voltage would have remained constant then your picture would have been like this. This is for one value of base width and this is for another value of base width. Now, if this is the new picture the area under this has reduced all this area as remained same. So this area reduces the recombination in the base reduces. But the base current is the sum of the recombination here plus the current here. So the total current would then have reduced but we are maintaining I_B constant. So the only way the maintaining I_B constant therefore is that this point should slightly shift up so that here this also slightly shifts up. So the total recombination now in the emitter and in the base still remains constant. This is the reason why the base voltage has to increase slightly whenever the collector to emitter voltage increases.

However, please note that the change in base emitter voltage is really very slight because the recombination current in the base is very small particularly in modern transistors. That is why in fact in many modern transistors you cannot really distinguish between the characteristics I_B V_{BE} characteristics for different values of V_{CE}. That explains the input characteristics. Let us look at the slide; we must be aware of the order of the values of currents and voltages involved. So V_{BE} is about 0.6 V where the magnitude of V_{BE} is 0.6 V_{BE} is negative because it is a p-n-p transistor, around 0.6 the current starts raising as it happens in any diode and the order of the current that is the base current is in tens of microamps. With this we have completed the DC characteristics of the p-n-p transistors.

Like we have discussed the common emitter characteristics you also have the common base and common collector characteristics. Now you can read about these characteristics yourselves and can even develop these characteristics in the way we have done for the common emitter. What we will do now is discuss the small signal equivalent circuit. Let us look at the slides that we showed related to small signal equivalent circuit of the transistor. First we discuss the so-called h-parameter model.

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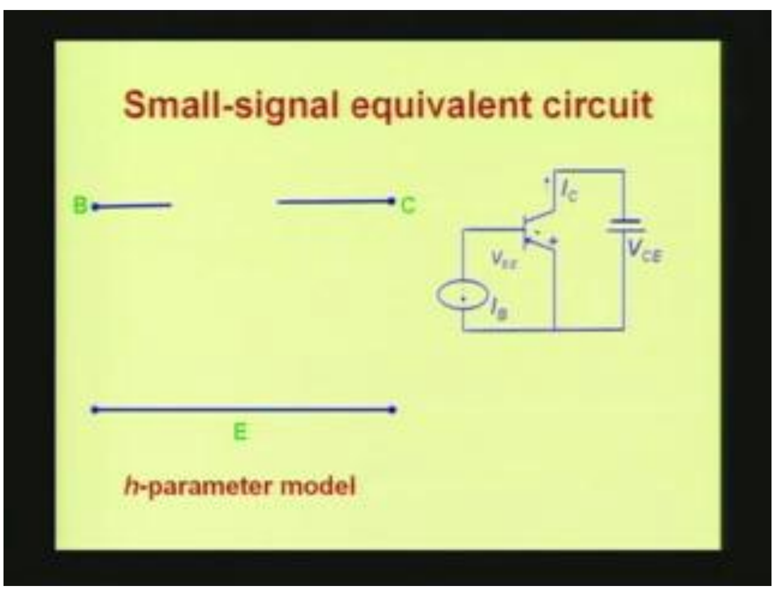

This model is applicable for low frequencies. The circuit diagram is shown. In fact we can relate the h-parameter model to the DC characteristics that we just discussed. Now what is happening here is you are incrementing the base current by a very small amount so the increment is indicated as lower case i suffix lower case b. So these lower case letters indicate the increment.

When you increment the base current by a small amount what are the effects?
First is an increment in the emitter base voltage. The increment in the emitter base voltage because of increment in I_B can be easily seen from the input characteristics which are shown here. Now this effect will be shown in the small signal equivalent circuit as a resistance between the base and emitter. So this resistance is called h_{ie}. The suffix i stand for input and in the suffix e is stands for common emitter. We are discussing the common emitter h-parameter model. Because of a small increment I_B there is an increment in emitter base voltage. This effect can be readily shown as a resistor. When I_B passes through h_{re} you get a small emitter base voltage.

Next there is an increment in collector current also because of the increment in base current. This increment in collector current because of increment in base current is shown on the output characteristics. These are the output characteristics where you find that the collector current increases when you increase the base current.

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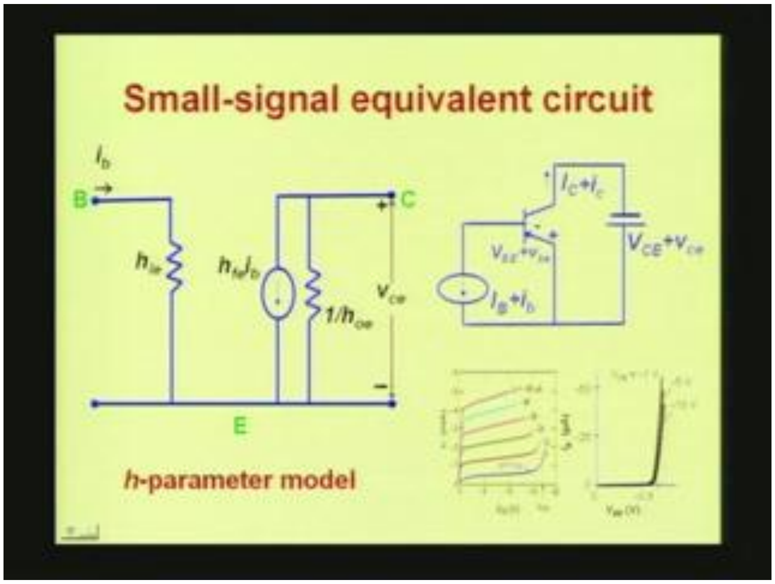

So this effect is captured in the equivalent circuit using this current source. The current flowing in the collector because of a change in the base current is $h_{fe}(i_b)$. Actually this is beta(i_b). The symbol h_{fe} stands for the e suffix e again stands for common emitter and suffix small f stands for forward gain. So input to output gain, input to output means forward. Next is, supposing you make an increment in the output voltage, so far we have made an increment in the input side but now let us make an increment on the output side. So, in the output side you have the collector to emitter power supply and if you make a small change in the collector to emitter voltage then what is the effect?

You have two effects: One is there is a change in the collector current. So, the change in collector current because of the change in V_{CE} is reflected by this particular resistance. So change in I_C because of change in V_{CE}, So, the change in current between any two terminals because of a change in voltage between the same two terminals is represented by a resistance. This is also shown on the output characteristics. Basically what it means is that when you change your V_{CE} there is a change in the collector current. So the slope of these curves is the effect that is captured by this particular resistance.

Now this resistance value is 1 by h_{oe}. The parameter hoe again means small e stands for common emitter and this suffix o stands for output. Since, h_{oe} has the units of 1 by resistance then 1 by h_{oe} will have the unit of resistance so both these components are derived from the output characteristics. Now this particular component here, the effect of V_{CE} on the input side there is a small effect. So there is a change in the emitter base voltage because of the change in the collector to emitter voltage. Now, this is reflected by the input characteristics here by the small change in the current when you change the collector to emitter voltage keeping the base current constant. That is a very small change in the base to emitter voltage. So this dispersion in the input characteristics is reflected by this particular source. So it is h_{re}, here the suffix e stands for common emitter and suffix r stands for reverse gain or reverse feedback because the change in the output is making a change in the input. Therefore this is a reverse. Whereas when the change in the input creates a change in the output we have the suffix f here for forward gain.

Now in practice this effect h_{re} is really very small because in modern transistors you cannot really distinguish between these characteristics here on the input side. Therefore the normal common emitter h-parameter equivalent circuit has only three parameters h_{ie}, h_{fe} and h_{oe}. Now, how do you derive the equivalent circuit from the device Physics? So far we have derived the equivalent circuit from the terminal characteristics. We have shown how in the output characteristics the changes in the currents and voltages are reflected on the equivalent circuit on the output side and how the changes occurring on the input characteristics are reflected on the components of equivalent circuit on the input side. This is one way of deriving the equivalent circuit. But we can derive the same equivalent circuit from the device Physics. Let us see how we can do that.

Let us look at our transistor. When you make a change in the emitter base voltage this is emitter, this is base and this is collector. Now, when you make a change in the emitter base voltage there is a change in the emitter current. So this can be represented by a resistance. Also, there is a collector current flowing here which is controlled by the emitter current. We can also regard the collector current to be controlled by the base current. Or as we did write in the beginning we could regard the collector current to be control by the emitter base voltage and that is when the device is viewed as a transconductance amplifier. So no matter which way you view there is a current source here. There are three ways of showing this current source. You can either call it alpha(i_e). Now I am showing the incremental changes. So normally the incremental quantities or the small signal quantities are indicated by lower case letters.

Here we can show v_{eb}, this is a p-n-p transistor. We are considering a p-n-p transistor. So, in response to v_{eb} there is an IE and there is an I_C. This I_C is equal to alpha(i_e). Or you could also write the same thing as beta(i_b). This is another way of writing the same thing because when you have i.e. you also have i_b. Alternately you could also show this current as the transconductance effect. That is, you can show this current as $g_m(v_{eb})$. These are the three ways in which we can show this current. So, change in the collector current is because of change in the collector to base or collector to emitter voltage. That is the base width modulation effect and that effect can be shown as a resistance. In fact this resistance should be shown within the device so we will slightly extend this and this p is now shifted down. And now the base width modulation effect is shown as a resistance here between collector and base. You can also show the same resistance, not the same value but this resistance because of base width modulation between collector and emitter when it is a common emitter amplifier.

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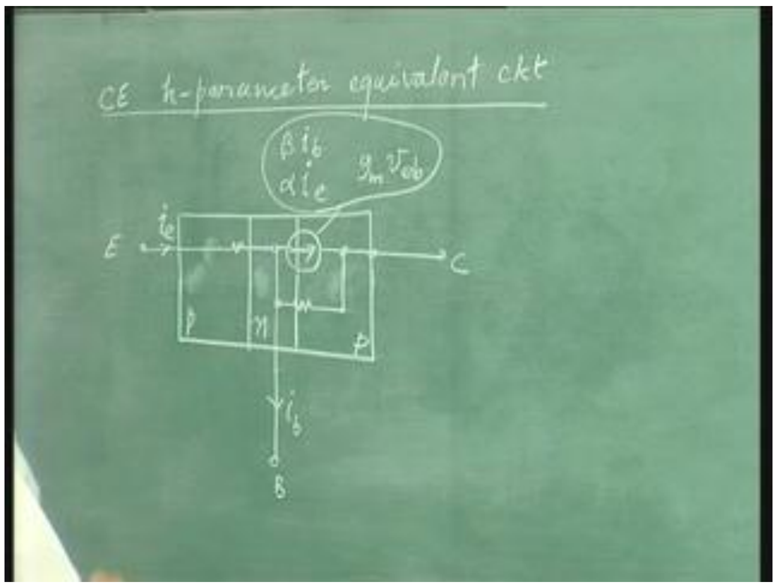

This is the basic circuit. Starting with this circuit how do you arrive at the h-parameter equivalent circuit we showed there?
Now, the first step is to recognize that you can show this resistance either in the emitter lead or in the base lead. So let us look at this circuit alone. This is e, this is b and this is c, i_b, i_e, alpha i_e. Now if I shift this resistance here, let us call this resistance as re an emitter resistance between base and emitter. If you shift this resistance in this lead then the same equivalent circuit looks like this.

Now you must ensure that the voltages and currents are same in both these circuits and only then this circuit is equivalent to this. To do that you recognize the fact that the base current is emitter current divided by beta plus 1. So i_b is equal to i_e by beta plus 1 or i_e is beta plus $1(i_b)$. Therefore this emitter base voltage which is small re into i_e can also be written as small re into 1 plus beta into i_b. Therefore if you shift this resistance in the base lead and if this current is i_b and you want to get the same voltage then this resistance is re into 1 plus beta.

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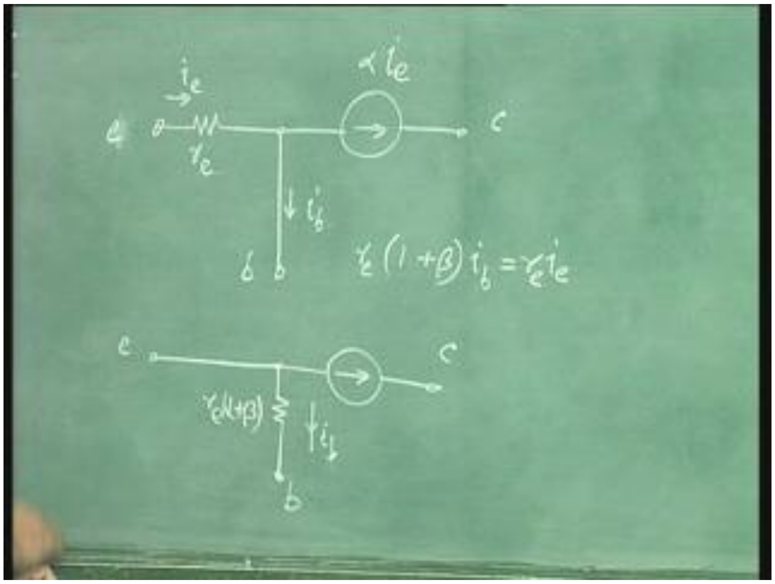

So this is emitter, this is collector and this is base. Now, the advantage of this circuit is, here the emitter seems to be common to collector and base. So, for common emitter configuration one can start with this as the basic equivalent circuit. Now if you redraw the same thing it will look like this. Now I put the emitter terminal here and shift the base terminal there then it looks like this which can also be redrawn as follows: So this is your emitter, this is the base and this is the collector.

Now note here that this current is outward when the base current is outward. So, the normal convention is, you show the current that will flow here if the input current is into the terminal. That is the reason why in the h-parameter equivalent circuit we show as this one here coming down and this increment is shown going in. So this is the current which you will call as $h_{fe}(i_b)$ and this is your h_{ie}. You can compare this with equivalent circuit that is shown on the slide. You can see the h_{ie} and h_{fe} i_b over there. As we said that because of base width modulation there will be a change in the collector current so that base width modulation resistance is now put in parallel with this current source. So, that same resistance was here, it showed the base width modulation and then it came here.

Of course when you do this transformation also this value of the resistance may change. But right now we are not concerned about the magnitude. First let us qualitatively see the arrangement of the components as to how it arises. Now this resistance is here and this resistance has basically come here. This is how one gets this h-parameter equivalent circuit. Now some students may have some doubts about the h-parameters. These h-parameters are discussed in your networks and system scores.

So please review the material related to h-parameter there if you have some difficulty about this system of h-parameters used to represent the input and output relations of any system. But otherwise you understand how from physical considerations you can get this equivalent circuit and how you can develop this equivalent circuit starting from the basic operation of the transistor as we discussed. And as we said, you can also develop the same equivalent circuit from the terminal characteristics. Now let us do a numerical exercise. Let us find out the measured output characteristics for the output characteristics we showed.

What are the values of the components of h_{ie}, h_{fe} and 1 by h_{oe}?
For this purpose we should look at the slide which shows as the output characteristics. Now we will have to choose some bias point because the values of the components are sensitive to the bias point. Let us say we choose this bias point where V_{CE} is minus 5 V and the corresponding I_C is about minus 1.3 mA. So our bias point is V_{CE} is minus 5 V, I_C is minus 1.3 mA, we will assume that temperature is 300 K. Further, we said the frequency because this is a small signal equivalent circuit small signal characteristics so we are applying a sinusoid basically hence we should know the frequency. This h-parameter equivalent circuit does not contain any capacitors. So this equivalent circuit is use for low frequencies. Let us say f is 1 KHz, this 1 is the typical value of frequency that can be regarded as low.

Now let us start with the parameter h_{ie}, that is this parameter here. Now this resistance is the same as this resistance which is nothing but this resistance here that is small re into 1 plus beta. And what is this small r_e?
If you go back here this resistance of the emitter base junction is the small r_e. Again you can understand in terms of this equivalent circuit. This small r_e is nothing but, you know from diode theory, small signal equivalent circuit of a diode, the small signal resistance is equal to the thermal voltage by the DC current that is flowing. Now this I_E is approximately equal to I_C because the alpha is very close to 1 for practical transistors this I_E is very close to I_C. So we can say this is also approximately equal to V_t by I_C. In fact strictly speaking if you want to write in terms of I_C then I_E is I_C by alpha. So you will have to multiply this by alpha. But this alpha is very close to 1 therefore we are removing this which is nothing but 1 by g_m so this quantity is same as 1 by g_m.

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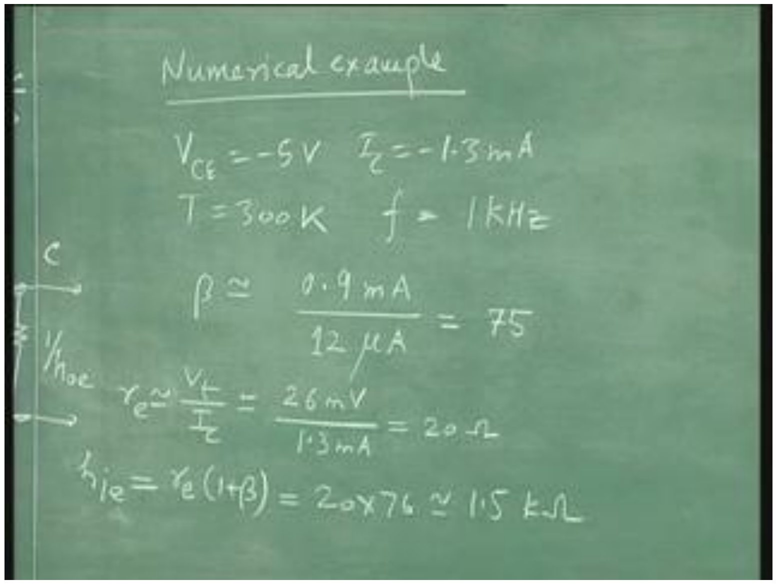

We can therefore find out this resistance re into 1 plus beta if you know the I_C which we have chosen as 1.3 mA and also the value of beta at this value of I_C. Please recall that beta varies with the collector current. So we must know the value of beta at the particular value of I_C that we consider.

Now what is that value of beta? Let us look at the output characteristics. The arrow here shows the increment in the collector current because of increment in the base current. The base current increment is 12 microamperes and you can see the increment in the collector current is this much. It turns out that it is approximately about 0.9 mA. So the beta value is 0.9 milliamperes by 12 microamperes. Now this is nothing but 75. So beta is above 75. Now V_t by I_C is equal to 26 mV at room temperature divided by 1.3 mA and this is equal to 20 ohms. Therefore your small r_e into 1 plus beta, and this V_t by I_C is actually approximately equal to small r_e. So small r_e into 1 plus beta is equal to 20 into 76 which is approximately 1.5 kilo ohms. So this is your value of h_{ie}. So this value here is about 1.5 kilo ohms.

Now the value of h_{fe} is nothing but beta. We have already estimated this which is 75. Now what is this resistance and how much is it? Now this hoe by definition is V_{CE} by i_c so change in collector voltage by change in collector current. Again you can determine this from your output characteristics. Let us look at this slide. The slope of this red curve at this point is the same as the slope of this triangle. You can see that the inclined line of this triangle is parallel to the red line. So what is the slope of this triangle? One can see that this particular width of the flat segment is 15 V and the change in the current for this 15 V is about ½ mA, this is about ½ mA. Therefore we can write the resistance 1 by hoe as 15 V by 0.5 mA that is 30 kilo ohms. So this resistance is 30 kilo ohms. So 1 by h_{oe} is 30 kilo ohms. This gives you typical values of parameters in an equivalent circuit. Now we said this is a low frequency equivalent circuit. There is another equivalent circuit which is used commonly at high frequencies. This is the so-called hybrid pie equivalent circuit or hybrid pie model. This circuit looks more complicated than the h-parameter model but can be developed very easily.

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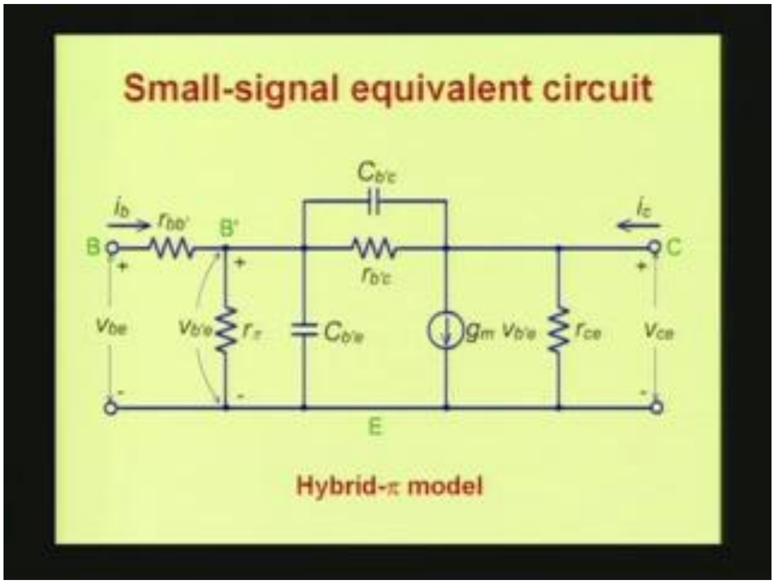

There are some important differences. As you can see there are some additional capacitances and resistances in this particular equivalent circuit. And also the current source has been shown to represent the transconductance effect. So it is shown control by emitter base voltage rather than base current as it happens in an h-parameter model. Now let us develop this particular equivalent circuit and see what the various components represent. So, if you look at your h-parameter equivalent circuit here this resistance h_{ie} is being called r_{pi} in the hybrid pie model. Let us mark the terminals base, emitter and collector.

Similarly, this source h_{fe} i_b is shown as controlled by the emitter base voltage. Therefore it is called g_m V_{be}. This particular resistance is called collector to emitter resistance so it is r_{ce}. Then you have capacitances. Now what are the capacitances? Let us look at the device. You have the emitter to base junction capacitance and you have the collector to base junction capacitance. So these two capacitances can be shown here as this capacitance and this capacitance. So this is C_{bc} base to collector junction capacitance and C_{be} base to emitter junction capacitance and this is the emitter.

Now if you look at the slide you will find a resistance here between base and collector. Before that you find here this terminal is being called B prime rather than B. Now we will shortly see why this is called B prime and what is the difference between B prime and d? So you can right now assume that this resistance is r_{bc} instead of $r_{b\ prime}$, later on we will convert the B to B prime. So what is the role of this resistance? The role of this resistance is the same as the role of the h_{re} parameter in the h-parameter equivalent circuit. Let us look at that circuit. Here there is a voltage source which we neglected. This is a very small effect we said. If you want to include this effect you will have to take this parameter into account.

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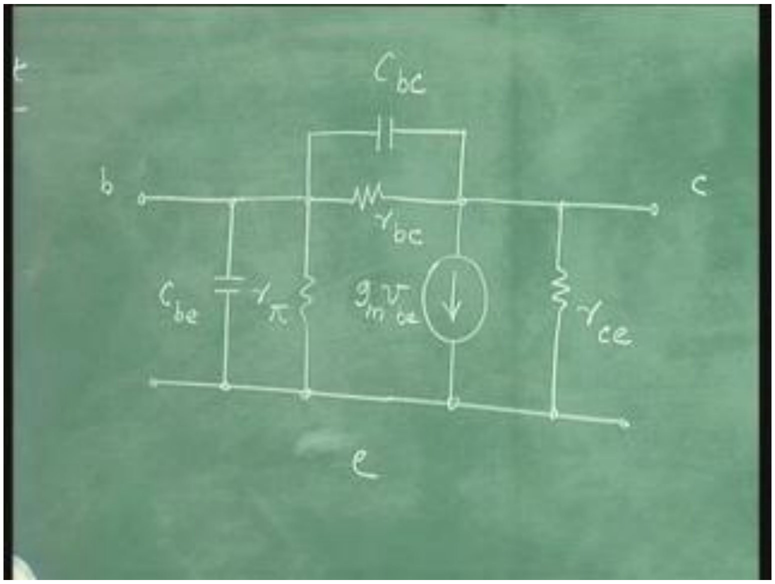

So in practice this h_{re} is of the order of 10 to the power minus 4 which is really very small. But still if you want to represent this effect then in the hybrid pie equivalent circuit this resistance $r_{b \text{ prime } c}$ is introduced. So you can see because of this resistance if there is a change in the collector to emitter voltage there will be a change in the emitter to base voltage because of the voltage division between this resistance and this resistance. So that is the role of this resistance. It is really the h_{re} of the h-parameter equivalent circuit. So we add this resistance here.

Right now this terminal is b. Now let us see why this terminal is called B prime and why between B and B prime there is a resistance. In other words, if you look at the slide we now want to explain why this resistance $r_{bb \text{ prime}}$ is present. For this purpose you must look at the structure of the practical transistor. So far we have been dealing with an idealized transistor structure one dimensional structure. Using the one dimensional structure we cannot explain $r_{bb \text{ prime}}$. And in high frequencies even small resistances become important because these resistances together with the capacitances give raise to time constants.

So let us look at the structure of the transistor which we have drawn in the first of this particular bipolar transistor discussion. This is how typical structure will look like. This is the emitter, this is the base and this is the collector. Now, of course you will have substrate which will be heavily doped. We are considering a discrete transistor. This is where you have the base contact, this where you have the emitter contact and this is where you have the collector contact. Now, how does a base current flow? The base current flows in this direction here. Since this region is very thin we have said that the base width is of the order of a micron in modern transistors. Since this region is very thin and long when the base current is flowing in this particular region it encounters a voltage drop. So this thin and long region has a resistance. Therefore the voltage drop here between base and emitter will not be the same as voltage drop here and that is the effect of this.

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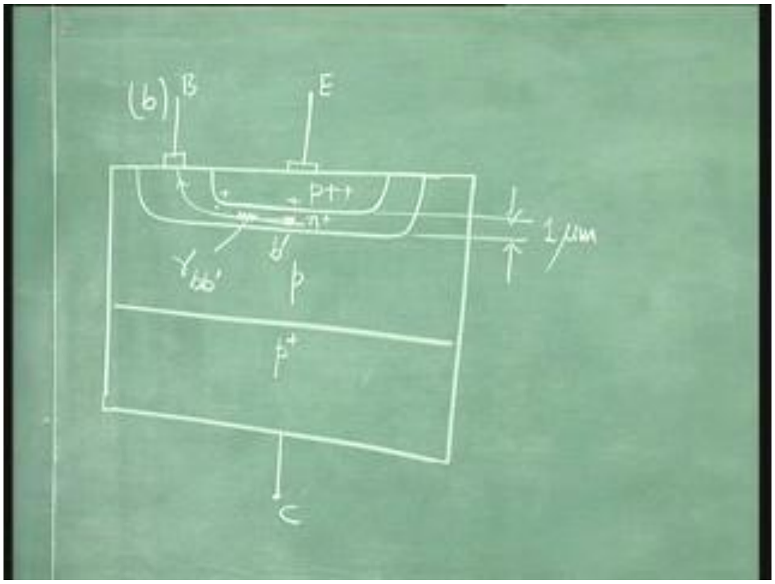

So this resistance is called $r_{bb\ prime}$ and what we do is, therefore this terminal is called the base the external terminal and the internal base terminal which is the end of this resistance here is called B prime. This is b or B. In the equivalent circuit we are using lower case letters because we are talking about small signal equivalent circuits. This terminal is b and the internal terminal of the device is called B prime. So there is a resistance between the external terminal and the so called internal base. This resistance is what is shown here and now you call this terminal as B prime and accordingly you change the letters everywhere. So this capacitance will be called $c_{b\ prime\ e}$, this capacitance is $c_{b\ prime\ c}$, this resistance is $r_{b\ prime\ c}$, this voltage is $v_{b\ prime\ e}$. This is how you get the hybrid pie equivalent circuit.

What are the values of the various parameters in this circuit?
Whenever you encounter a parameter you must know the typical value of this parameter and also the unit. Since we have done the exercise for h-parameter equivalent circuit from there we can easily identify the fact that is r pie is nothing but h_{ie} which was 1.5 kilo ohms for the particular transistor we considered. So that is the order of the value for r pie. Now the g_m is nothing but I_C by V_t which is 1.3 mA by 26 mV. So this is 1 by 20 ohms. So 1 by 20 ohms is the same as 50 millisiemens which is the value of g_m. The r_{ce} is same as the 1 by h_{oe} so this was 30 kilo ohms. The $r_{bb\ prime}$ this resistance is of the order of 100 to 300 ohms in practice. In fact every effort is made to reduce this resistance. It is a very serious problem at high frequencies.

Later on we will discuss little bit about the hetero-junction bipolar transistor and we will explain the role of this transistor. This transistor is an advanced transistor which is used to avoid some of the problems which we encounter at high frequencies for this simple bipolar transistor and one of the problems is the $r_{bb\ prime}$. Then what are the values of $c_{b\ prime\ e}$? The capacitance $c_{b\ prime\ e}$ is of the order of about 20 Pico farads so tens of Pico farads is the typical value. This capacitance is smaller and is of the order of two Pico farads.

Please note that collector to base junction is either 0 or reverse bias whereas the emitter base junction is forward bias. That is why this capacitance is more. You recall the discussion on the capacitance. Capacitance of the forward bias junction is always more than the capacitance of a reverse bias junction. Now $r_{b\ prime\ c}$ is really a small resistance and it is of the order of tens of mega ohms. With that we have completed the discussion of the hybrid pie equivalent circuit. This is used at high frequencies because it is more convenient to work with this kind of a circuit when you are considering high frequencies. And by the same reason at low frequencies these capacitances and so on and $r_{bb\ prime}$ is not important. Therefore you need not use this complicated equivalent circuit at low frequencies and that is where we use the h-parameter equivalent circuit.

Now students have one doubt and this should be clarified. Why change over to this particular scheme of representing the current source as controlled by the emitter base voltage rather than as controlled by the base current as we do in the h-parameter equivalent circuit?

Now the reason for this is very important. Please note that if this currents were shown as controlled by the base current, that is the base current is the current flowing in here, then it would mean that the current here is because of the current here as well as the current here as well as the current in this lead and the current in this lead because the base current here would flow into the capacitance through the resistance and so on. There are so many components at this node.

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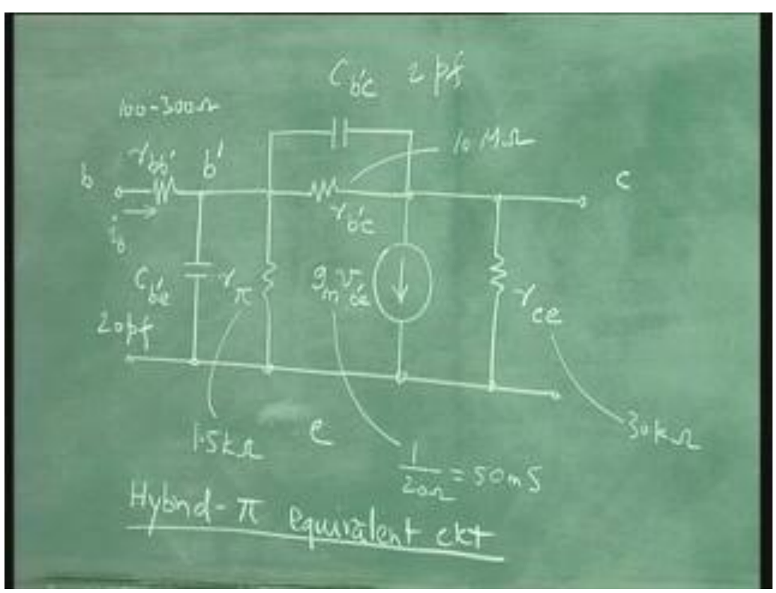

Now in practice, however, the transistor action is only there or the transistor action transfers only the current in this particular resistance to the output. It does not transfer the current through the capacitance to the output. Basically the transistor action only transfers the current through the resistance to the output. Therefore it will be erroneous to show this currents source to be controlled by base current because then it would mean that this current is also control by the current to the capacitance and resistance. So, to avoid this problem we must show this current source as control only by the emitter base voltage then the effect of the capacitance is not coming in this current which is how it should be and effect of other components also is not coming. With that we complete the discussion of the bipolar transistor. Let us quickly summarize what we did in these lectures on bipolar transistor.

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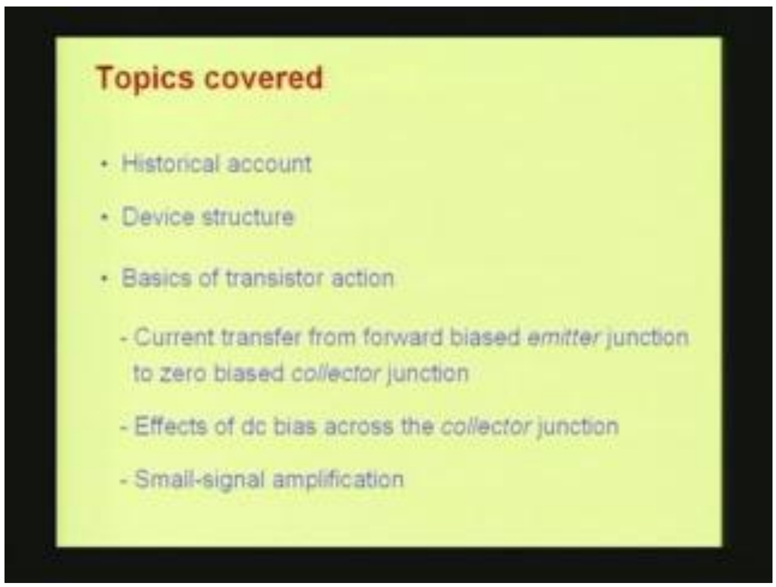

First we looked at the historical account of how this device came into being, then we discuss the device structure. Then we idealized this structure and using this idealized structure we discuss the basics of transistor action. We discussed how the current transistor occurs from forward bias emitter junction to zero bias collector junction.

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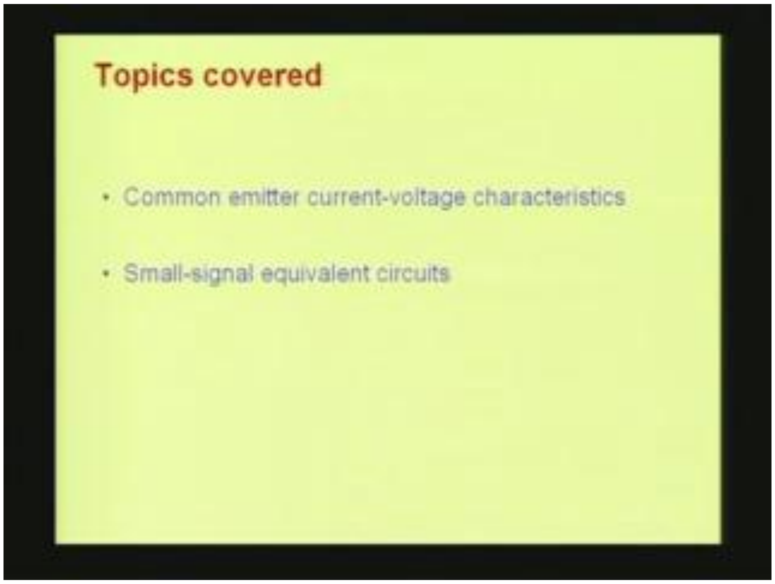

Then we saw the effects of DC bias across the collector junction. Then we consider the small signal amplification. We came to the common emitter current voltage characteristics which we discussed in detail, these are the DC characteristics. And then finally we considered the AC characteristics or small signal equivalent circuits.