Basic Electronics
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Lecture – 28
BJT amplifier (continued)

Welcome back to Basic Electronics. In this lecture our main focus is the small signal equivalent circuit of a BJT. First we will explain the meaning of the term small signal condition. We will then derive the most basic form of the BJT small signal model. And explain how it is related to the bias quantities, in particular the bias value of the collector current. So, let us begin.

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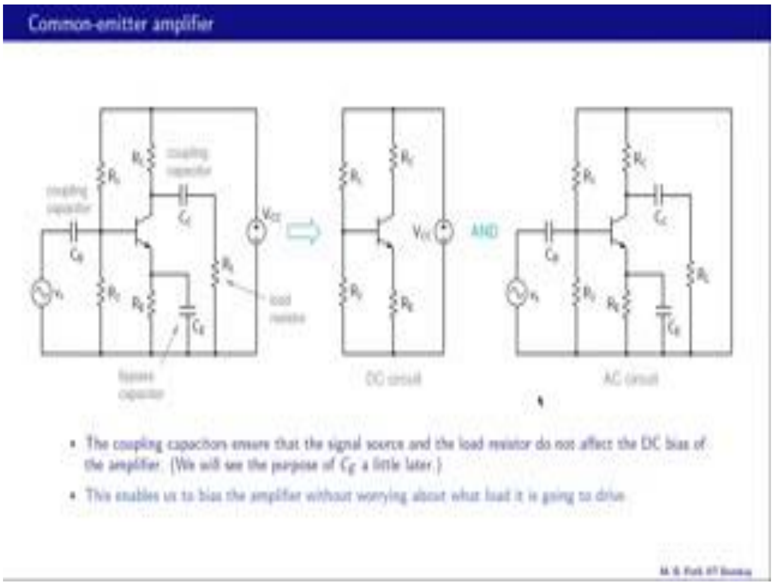

We are now in a position to look at the complete common emitter amplifier circuit shown here. And remember that we have actually considered this part earlier already when we look at biasing of the amplifier, and now all of these things are added on top of it. So, there is a coupling capacitor here going to the source voltage then there is another coupling capacitor and that is how the load is connected the load resistor. And there is a third capacitor which we call the bypass capacitor and that is going from the emitter to the ground. We will treat this as the common reference node or the ground. And now let us see what the DC circuit for this amplifier is and the AC circuit for the amplifies.

Thus the DC circuit and how do we get this. We recall that the capacitor is an open circuit in the DC situation. So, this capacitor is an open circuit and so is this and this. So, therefore, this R L is not essentially, not in the circuit V s is not in the circuit and this is an open circuit and that boils down to this circuit here. Then that is the DC circuit what about the AC circuit, AC circuit is here the resistors remain as resistors as we have seen earlier, capacitors also remain as capacitors. The AC source remains as AC source, and the DC source it is replaced with the short circuit. So, that is what we have got for the AC circuit.

What about the transistor. That is still big a question mark and we have to of course, tackle that question V s 1 otherwise we really cannot proceed further, but what we see already is that this DC circuit is identical to the one that we considered when we talked about biasing. So, the coupling capacitors ensure that the signal source and load resistor do not affect the DC bias of the amplifier and that is a very big advantage because we do not need to worry about what we are going to have as a load resistance or what source voltage is going to drive this amplifier, when we deign the biasing components. And as we said let us look at the purpose of CE a little later that is not a coupling capacitor that is a bypass capacitor, and just repeating it once again this fact that the DC circuit is not affected by either V s or R L enables us to bias the amplifier without worrying about what load it is going to try.

So, that is a big benefit and the next step now is to look at what this AC circuit how that can be simplified.

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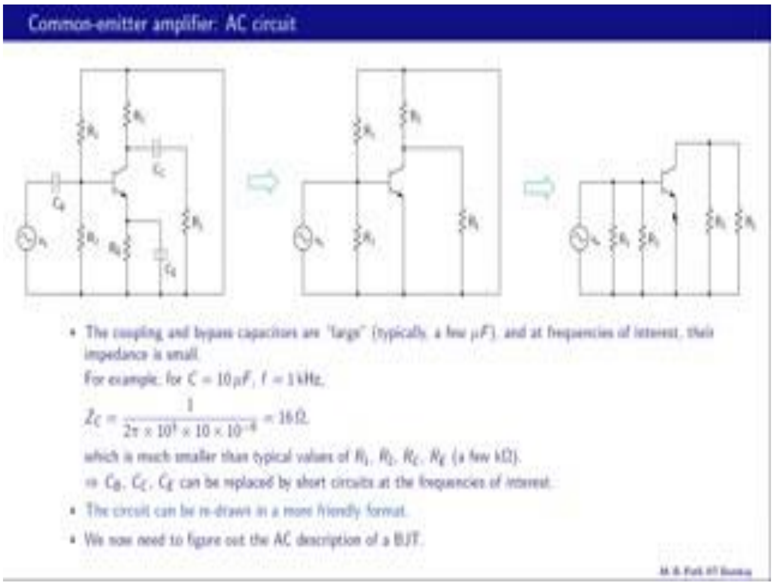

Here is the AC circuit once again. Now it turns out that the coupling and bypass capacitors are large typical a few micro farads R 1 tens of micro farads. And at the frequencies of interest their impedance turns out to be small. Let us take an example say c is 10 micro farads and f is 1 kilo hertz at this frequency the impedance of the capacitor is one over omega c in magnitude. Omega is 2 pi times one kilo hertz and c is 10 times 10 raise to minus 6. So, that turns out to be only 16 ohms. And this impedance is much smaller than typical values of the resistances in the circuit like R 1, R 2, R C, RE which are in the range of a few kilo ohms. And therefore, what we can do is we can replace these capacitors CB, CC and CE with short circuits because their impedance is so, small. And let us see what we get in that case.

So, this is what the circuit reduces to. What have we done we have replaced CB with the short circuit CC also with the short circuit and CE also with the short circuit. And because of that what has happened is this emitter has got effectively connected to the ground directly bypassing this RE resistor like that. And now it is clear why this capacitors CE is called the bypass capacitor.

Now, this circuit can be redrawn in a more friendly format and let us do that like that. And let us first check that these 2 circuits are actually the same. Let us start with the transistor. Here is a transistor from the base we have V s going to ground R 1 going to ground and R 2 going to ground. What about this case? Here is the base here R 2 going to ground V s going to ground and R 1 also going to ground, because we have a short circuit here. What about the collector? From the collector we have R C and R L connected in parallel and going to ground. Here from the collector we have R L going to ground and also R C going to ground. And the emitter is connected directly to ground in both cases all right. So, these 2 circuits are indeed identical and we can proceed further.

The next question now is, what is the AC description of the BJT? So, let us look at that in the next slide.

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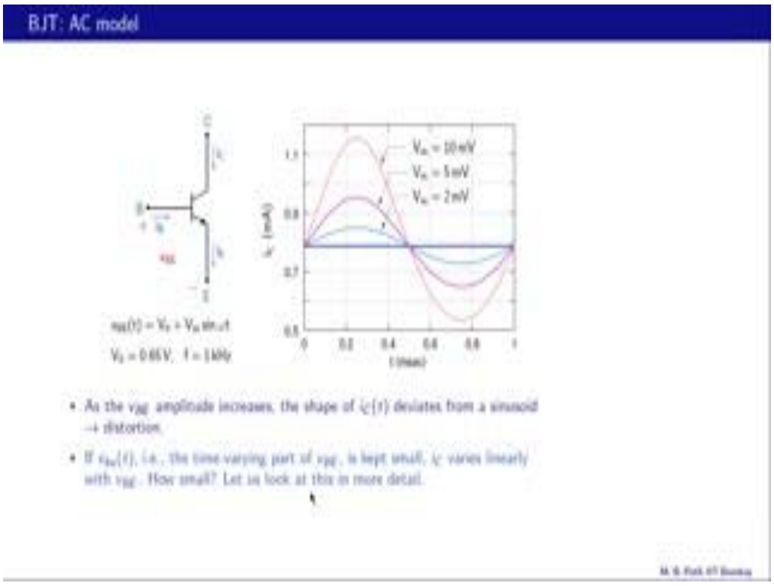

So, the question we want to answer now is what is the transistor behavior when a sinusoidal input voltage is applied and super imposed on DC bias value. In particular, we will look at the base emitter voltage of this form, where V0 is a constant, let us say 0.65 volts corresponding to a forward bias. And on top of that there is this sinusoidal id with the frequency of let us say f equal to one kilo hertz. And in this graph we have plotting I C the collector current, the total collector current as a function of time. And we are only showing one cycle of the input waveform which corresponds to one millisecond. Let us look at these curves one by one.

So, this is blue curve corresponds to V BE equal to V0, and with now sinusoidal part there. So, it is just V0 constant. And that is why the collector current is also a constant. If you apply VB equal to the same constant plus Vm sin omega t with Vm equal 2 millivolts, this is what. We get if we increase that amplitude Vm to 5 millivolts this is what we get. And if we increase it further to 10 millivolts this is what we get. And as we are looking at these closely you will surely notice some difference in the shape of these 3 curves. As V BE varies with time we expect I C of t also to vary with time, and when V BE increases above the base value V0 then I C will go above this base value that is the DC collector current corresponding to base emitter voltage of V0. And when the base emitter voltage goes below V0, then we expect the collector current to go below that I C, DC value here and that is what is happening.

Now, in this case when V emits 2 millivolts, we can see that these positive and negative excursions are equal and that is what the sinusoid should like. But if we increase Vm to 10 millivolts we see that this positive excursion is larger this difference here than the negative excursion. And clearly therefore, there is some distortion in the collector wave form for Vm equal to 10 millivolts. So, that is the first point we make. As the VB amplitude increases the shape of I C t deviates from a sinusoidal and that causes distortion.

Now, suppose we want to write an equation for this I C of t only the time varying part of this I C of t. What would that look like? It would be sinusoidal and it is amplitude would be that height over there. So, it would be some I C cap sin omega t. And that is exactly the same form as the time varying part of the base emitter voltage. So, in other words the time varying parts or the sinusoidal part of the collector current and the base emitter voltage are proportional to each other. And that is the second point we want to make. If V BE of t that is the time varying part of V BE is kept small when I C varies linearly with V BE. And the next question that arises is how small. Let us look at that in more detail in the next slide.

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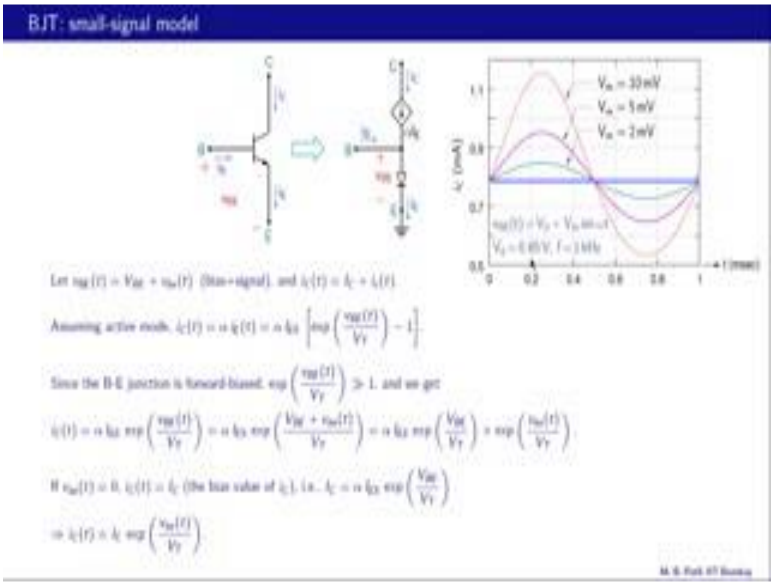

Here is the graph again of the collector current versus time. And the base emitter voltage is constant which is 0.65 plus Vm sin omega t and the frequency is one kilohertz. And the base collector junction for these calculations was assumed to be under reverse biased, the exact value of the reverse bias is of course, is not important. Now in these conditions that is in the active mode or in the linear region the device model as we have seen before is given here; the base emitter diode and then the controlled current source. If this is IE that is alpha times IE. So, we are of course, very familiar with this model manner.

Let us start with V BE in the instantaneous base emitter voltage equal to the constant part and the time varying part. In this case Vm sin omega t and the constant part of course, we call as the bias and the time varying part is the signal. And similarly the collector current also would be a constant part plus a time varying part. And assuming active mode the collector current is alpha times IE of t. And what is IE? It is IES e raised to be V BE by V T minus one this is the total instantaneous base emitter voltage that is the total instantaneous emitter current and this is of course, simply special case of the Ebers moll model as we have seen earlier.

Now, since the base emitter junction is forward biased, this term will be much larger than this one here, and we can simply ignore that one and get I C of t is equal to alpha times IES times exponential V BE divided by V T. This is same as that one except we are not written that one there equal to alpha times IES. Now this V BE the instantaneous voltage we are going to substitute with V BE plus the busy part plus the time varying part like that. And now this is like e raise to a plus b which is e raise to a times e raise to b and that brings us to this equation I C of t is alpha e s times e raise to V BE by V T this is the constant V BE or the biased value of V BE times e raise to V BE of t divided by V T this is the time varying V BE this part here.

now if V BE the small case of small b e is 0 if this time varying part is 0 then what do we have for base emitter voltage it is simply this constant value in our example 0.65 and then if we substitute that here I C of t this becomes one and we are left with alpha times IES times exponential V BE by V T. So, 0.65 divided by V T and that is the bias value of I C with no signal and that is shown here in the dark blue curve just constant straight line. So, if V BE is 0 if the signal is 0 then the total instantaneous current collector current is the bias value of the collector current that is I C capital I of capital C the DC part of I C here is alpha time IES times e raise to V BE by V T.

And now this part is also appearing here and therefore, we can say that I C of t is instead of writing this expression, we just write I C and that multiplied by e raise to V BE by V T, where V BE is the signal V BE. So, from all of this algebra we get I C of t that instantaneous collector current is the DC or bias collector current multiplied by e raise to V BE of t divided by V T. So, in this term there is only the time varying component of V BE, in this term there is only the constant component of V BE. Let us remember that and let us go further with this.

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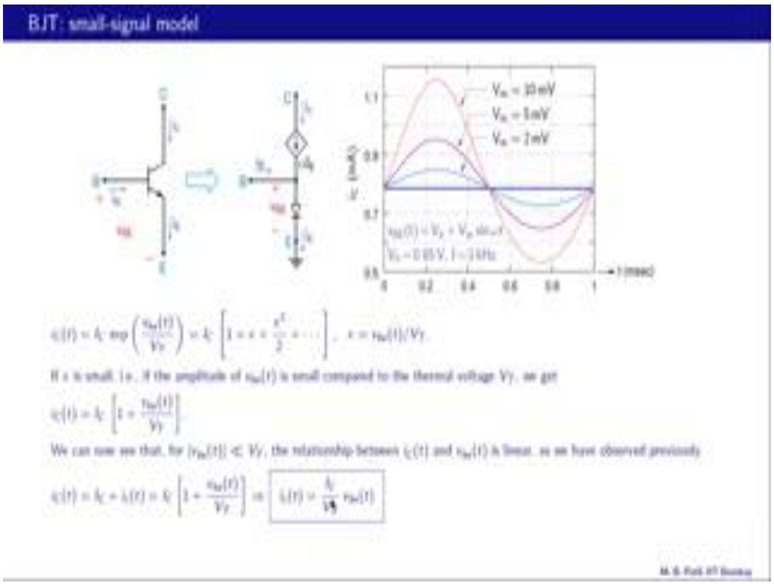

Here is the relationship between I C and V BE. Once again this quantity is the total instantaneous collector current it includes the both DC and the signal collector current. This capital I sub capital C is the DC or biased value of the collector current, this V BE is the signal base emitter voltage, it does not include the bias or DC base emitter voltage all right. Let us now take a specific example say, this one, where V BE is given by Vm sin omega t with Vm equal 2 millivolts. Let us define a variable x as V BE by V T where V T is the thermal voltage 26 millivolts and VB of t in this particular case it is going to be limited to 2 millivolts in magnitude. So, this magnitude of x is always going to be smaller than 2 millivolts divided by 26 millivolts. Say one by 12 all right. Now what we will do is expand this e raise to x using the Taylors series and this is what we get. Since our x is small in magnitude compared to one we can ignore terms like x square by 2 x cube by 6 and so on as compared to x, and therefore we get I C of t as approximately equal to I C times 1 plus x.

So, in summary if x is small that is if the amplitude of V BE the signal part of the base emitter voltage is small, compared to the thermal voltage V T. Then we get I C of t the total instantaneous collector current equal to I C which is the DC or bias current times 1 plus x and x is V BE divided by V T. Let us now write the total instantaneous collector current as the sum of DC collector current and the signal collector current. So, this is our left hand side here. This is the right hand side.

The DC collector current cancels out and we get I C of t the signal collector equal to I C by V T where this I C is the DC or bias collector current times the signal base emitter voltage as a function of time. What does this equation say? This equation says that the signal collector current is directly proportional to the signal base to emitter voltage because these quantities are constants. Note that the collector current does depend on the base to emitter voltage, but only on the constant part of the base to emitter voltage, namely 0.65 volts in this case. So, this relationship looks like I C of t equal to k times V BE of t where k is simply a constant which does not depend on time.

What are the implications of this equation? It says that if x is small, that is if the amplitude of the signal base to emitter voltage is small compared to V T then the signal collector current is directly proportional to the signal base to emitter voltage. If V BE of t is sinusoidal as in this case and if the amplitude of V BE is small, then we expect the collector current also to be sinusoidal. And that is indeed what we observed in this case which corresponds to an amplitude Vm of 2 millivolts for the base to emitter voltage which is small compared to the thermal voltage about 25 millivolts.

Now, let us take this case where the amplitude of the base to emitter voltage is larger 10 millivolts. The maximum value of x now is 10 millivolts by 25 millivolts. That is 0.4 and that is not small any more with respect to one. So, what; that means, is we cannot ignore these higher order terms with respect to x. And that shows up as distortion over here. Now this condition in which the variation of base to emitter voltage is small compared to the thermal voltage V T is called the small signal condition. And it is very important to keep in mind that this equation which we have derived is only valid if the small signal condition is satisfied. So, it is under this condition that we will now derive the BJT small signal model.

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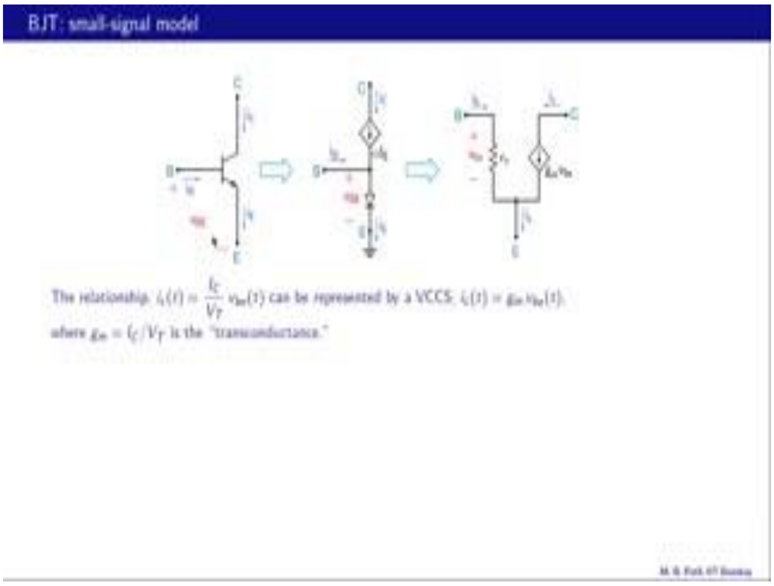

And that brings us to the small signal model of the BJT, and it is now clear why it is called small signal. Because the base emitter signals voltage must be small as compared to the thermal voltage V T. And then we have this relationship that we saw in the last slide.

Now, this equation can be rewritten as I C of t the signal part equal to V BE of t times gm where gm is I C by V T. Now gm is a constant because I C is a constant for a given bias condition that is for a given bias value of the base emitter voltage and V T is a constant. So, this gm which is the I C by V T is called the trans conductance parameter of the transistor. And it is very important to remember that it is not an absolute constant because it depends on the bias condition in particular it depends on the bias value of the base emitter voltage.

To summarize we have addressed a very important issue in this lecture namely the small signal condition in the context of a BJT and it is applications. We have derived the hybrid pi model of the BJT under the small signal condition. In the next class we will put all these findings together and look at the complete small signal circuit for the common emitter amplifier, until then goodbye.