# Basic Electronics

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## Lecture – 29
## BJT amplifier (continued)

Welcome back to basic electronics. In the previous class we have looked at the basic small signal model of a BJT. We will now add a few other components to that model to represent some effects we have not considered. So far we will then use the small signal BJT model to draw the complete AC circuit of the common emitter amplifier. So, let us begin.

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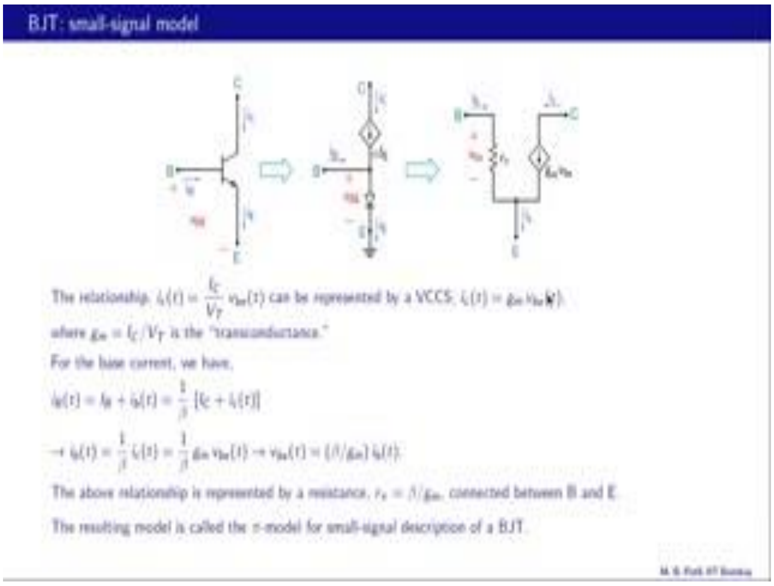

BJT: small-signal model

The relationship, $i_c(t) = \frac{I_C}{V_T} v_{be}(t)$ can be represented by a VCCS, $i_c(t) = g_m v_{be}(t)$,

where $g_m = I_C/V_T$ is the "transconductance."

For the base current, we have,

$i_B(t) = I_B + i_b(t) = \frac{1}{\beta}[I_C + i_c(t)]$

$\rightarrow i_b(t) = \frac{1}{\beta} i_c(t) = \frac{1}{\beta} g_m v_{be}(t) \rightarrow v_{be}(t) = (\beta/g_m)\, i_b(t)$.

The above relationship is represented by a resistance, $r_\pi = \beta/g_m$, connected between B and E.

The resulting model is called the $\pi$-model for small-signal description of a BJT.

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At this point let us take stock of the situation. We started with this n p n transistor. Then we replaced the transistor with it is equivalent circuit model using the ebers moll model under the special condition that we have linear region. And then we derived the small signal model which is i c equal to gm times V BE. And it is called the small signal model because it is valid under small signal conditions namely the base emitter signal voltage must be small compared to the thermal voltage V T. And then we proceed to the AC or the small signal model which is this one.

Let us look at this equation. What is it saying? There is a current which is controlled by a voltage. So therefore, this equation represents a voltage controlled current source and that is what we have shown over here, that is the signal current i c that is equal to gm times V BE, where V BE it is this voltage between the base and the emitter. Now we should remember that in this model we are only going to see AC or time varying quantities and not the DC quantities, but the DC quantities are implicit in this model because as we have seen gm is i c over V T and i c does depend on the bias conditions. So, therefore, the DC quantities are embedded in this small signal model.

Let us now proceed and get the other part of this model that is this one. For the base current we have i b the total instantaneous base current E is equal to the DC part plus the time varying part. That is one over beta times the collector current and the collector current again is the DC part and the time varying part. Now this DC terms cancel with each other and we are left with the signal currents i b equals to 1 over B on 1 over beta times i c. And i c the signal corrective current is gm times V BE as we have seen before. So, we put that here we get 1 over beta times gm times V BE or V BE equal to beta over gm times i b. Now this relationship is represented by a resistance Rpi equal to beta pi gm, connected between B and E the base and emitter like that. So, this V BE is equal to i b times Rpi that is the same as this equation V BE is equal to i b times Rpi where Rpi is beta over g m.

This resulting model is called the pi model for small signal description of a BJT. And in some older textbooks you might find some other names for these parameters like hie here hfe times i b here and so on. Those ever used because in the early days BJT was often thought of as a 2 port network one port being this one and the other one being this one and therefore, those h parameter definitions were used for these parameters. In modern text books these h parameters are getting increasingly replaced with Rpi and gm and it is best not to use the earlier parameters anymore.

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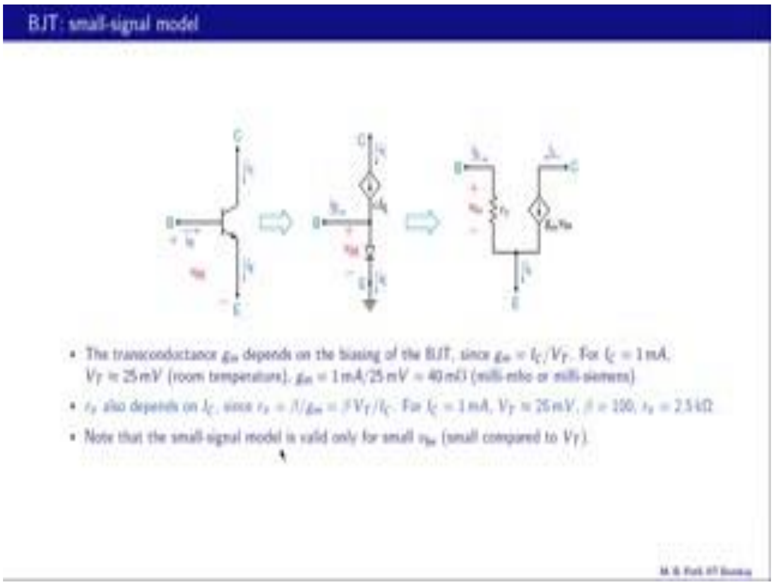

BJT: small-signal model

- The transconductance $g_m$ depends on the biasing of the BJT, since $g_m = I_C/V_T$. For $I_C = 1\,mA$, $V_T \approx 25\,mV$ (room temperature), $g_m = 1\,mA/25\,mV = 40\,m\mho$ (milli-mho or milli-siemens).
- $r_\pi$ also depends on $I_C$, since $r_\pi = \beta/g_m = \beta V_T/I_C$. For $I_C = 1\,mA$, $V_T \approx 25\,mV$, $\beta = 100$, $r_\pi = 2.5\,k\Omega$.
- Note that the small-signal model is valid only for small $v_{be}$ (small compared to $V_T$).

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Let us do a quick revision of the BJT small signal model. First the trans conductance gm this parameter depends on the biasing of the BJT because gm is i c over V T, where i c is a DC or bias collector current. For example, if i c is 1 milliamp and if you have room temperature then V T is about 25 millivolts then gm is 1 milliamp divided by 25 millivolts or 1 over 25-ohm inverse. Ohm inverse is the same as mhos it is denoted by this symbol looks like inverted ohm. So, that turns out to be 40 milliohms also called a milli Siemens.

The other parameter r phi also depends on the bias current i c. Since r phi is beta over gm that is beta times B t divided by i c, for i c equal to 1 milliamp for example, and the thermal voltage equal to 25 millivolts and beta equals to 100. If we do this calculation Rpi turns out to be 2.5 kilo ohms. And finally, we must always remember that the small signal model is valid only for small V BE small compared to the thermal voltage.

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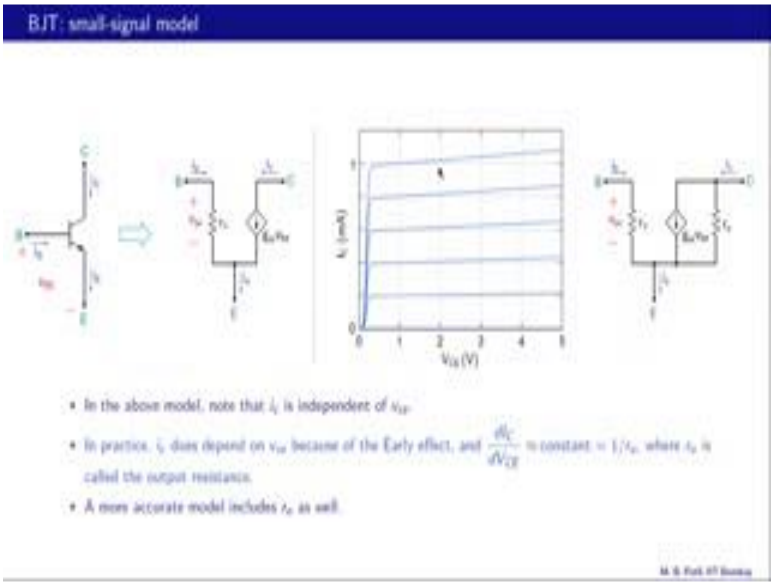

BJT: small-signal model

- In the above model, note that $i_c$ is independent of $v_{ce}$.
- In practice, $i_c$ does depend on $v_{ce}$ because of the Early effect, and $\frac{dI_C}{dV_{CE}}$ is constant $= 1/r_o$, where $r_o$ is called the output resistance.
- A more accurate model includes $r_o$ as well.

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The pi model that we have derived for the BJT under small signal conditions is fairly good accurate description of the BJT with the small signal approximation, but to that we would now like to add a correction, we might call that second order correction and that is the following. In the above model i c is independent of VCE. What is i c here i c is simply gm times V BE and there is no dependence on VCE. Now in reality that is not quite the case. There is a small dependence of i c on VCE and that is shown in this plot here.

What is this plot? It is i c versus VCE for various base current values as we have seen earlier. Now if you remember these lines the i c curves were perfectly horizontal in our earlier picture. And now we see some slope over here. And this is a more realistic description of BJT. So, in practice i c does depend on VCE because of the so, called early effect and d i c d VCE that is this slope here is approximately constant. That is given by one over ro where ro is called the output resistance. So, this slope here is given by one over ro. So, to this small signal model we need to make this correction by adding ro. So, more accurate model includes ro as well and that is what it would look like. So, we have now ro between the corrector and the emitter.

So, the signal current the signal corrector current would now be gm V BE plus this current and this current through ro accounts for this non 0 slope over here.

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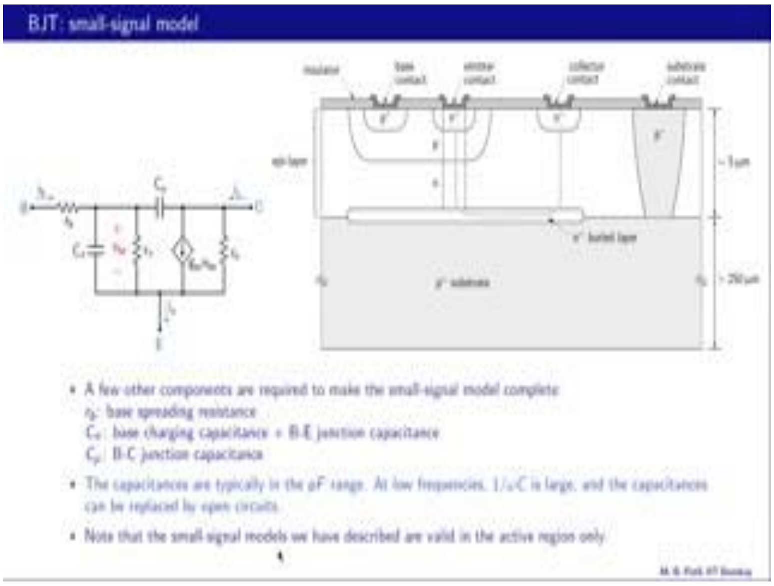

BJT: small-signal model

- A few other components are required to make the small-signal model complete
  $r_b$: base spreading resistance
  $C_\pi$: base charging capacitance + B-E junction capacitance
  $C_\mu$: B-C junction capacitance
- The capacitances are typically in the pF range. At low frequencies, $1/\omega C$ is large, and the capacitances can be replaced by open circuits.
- Note that the small-signal models we have described are valid in the active region only.

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We now want to add a few other components to our basic BJT small signal model, in order to make it more complete. And before we do that let us take a look at the actual fabricated BJT device. This is a cross sectional view of a BJT, which is inside an integrated circuit such as an opam. A discrete transistor structure would look a little different, but many of these features that we see in this structure are going to be common. So, let us look at this transistor structure.

First of all, let us locate the intrinsic device the n p n transistor. And that is here is our emitter contact that is the emitter n type region is called n plus because it is heavily doped. This is our base p region and that is our collector n region; so n p n that is our n p n BJT. So, this is our intrinsic BJT structure and because of technological constraints we cannot make a contact to the base region here or to the collector region over here.

And therefore, we need this rest of the structure and we will look at that soon, but before that let us take a quick look at the dimensions involved, this thickness the so, called epitaxial or the epi layer which n type is 5 microns now to put that in prospective the diameter of our hair is 50 microns. So, you can imagine how small that is the rest of the silicon vapor is something like 250 or 300 or 400 microns thick and to put that in prospective 250 microns is 1 4th of a millimeter. So, this entire thickness is relatively small.

Let us now briefly look at the base contact and the collector contact, the base contact is here and the region close to the base contact is heavily doped heavily p type, in order to make a good contact here. So, the base current flows from the base terminal or base contact to the intrinsic base region like that the collector contact is here, again the region next to that is heavily doped, n type to make a good contact. And the collector current flows through the device like that through this n plus buried layer and to the collector contact.

Now this buried layer is there in order to reduce the resistance in the path of the collector current, if we did not have this n plus layer than the collector current would flow like that. And this n region would present a larger resistance to the collector current. With this layer current path is predominantly like that and that is the small resistance because this layer is doped heavily.

In this small signal model, we have the base terminal here, which is this base contact in the actual structure. And then we have this note which corresponds to intrinsic base region. And between the 2 we have resistance called R B called the base spreading resistance. And that corresponds to the resistance between this 2, between the base contact and the actual intrinsic base region of the device, rb is typically small compared to Rpi. In addition, we need to include capacitor Cpi between the base and the emitter like that and that accounts for the base charging capacitance and the base emitter junction capacitance and what are the formulas for all of these that of course, you will study in semiconductor devices course.

In addition to Cpi we also have Cmu between the base and the collector. And that accounts for the base collector junction capacitance. This capacitances Cpi and Cmu are typically in the pF range and at low frequencies 1 over omega c the impedance of these capacitances is large and very often these capacitors can be replaced by open sockets. So, that can be replaced by the open circuit if the frequencies are not too large and that can also be replaced with an open socket. And last, but not the least let us always remember that the small signal models we have described this one as well as earlier ones are valid only in the active region and only under the small signal appropriation a very important point and sometimes easy to forget. So, for example, if the device is operating in the saturation region then we cannot use these small signal models.

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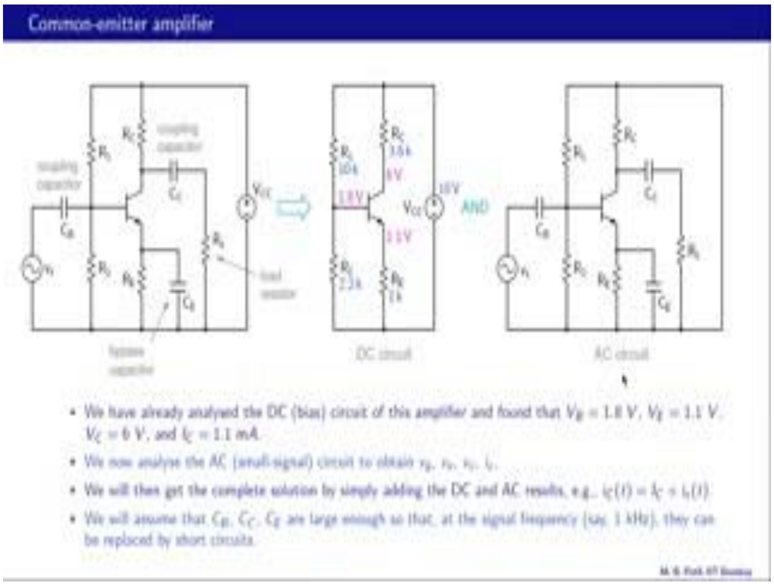

Common-emitter amplifier

- We have already analysed the DC (bias) circuit of this amplifier and found that $V_B = 1.8$ V, $V_E = 1.1$ V, $V_C = 6$ V, and $I_C = 1.1$ mA.
- We now analyse the AC (small-signal) circuit to obtain $v_b$, $v_e$, $v_c$, $i_c$.
- We will then get the complete solution by simply adding the DC and AC results, e.g., $i_C(t) = I_C + i_c(t)$.
- We will assume that $C_B$, $C_C$, $C_E$ are large enough so that, at the signal frequency (say, 1 kHz), they can be replaced by short circuits.

Let us now look at the common emitter amplifier once again the circuit here. And we have already analyzed the dc circuit on this amplifier or the bias circuit this circuit here. And we found that the base voltage was 1.8 volts the collector voltage was 6 volts and the emitter voltage was 1.1 volts. And collector current is 1.1 divided by 1 k assuming i c and IE to be approximately equal. So, i c turned out to be 1.1 milliamp. So, this is just a revision of what we already did. And we now want to analyze the AC or the small signal circuit to obtain all these signal quantities the base voltage the emitter voltage the collector voltage and the collector current.

And now of course, we know the meaning of small signal the base emitter voltage the signal voltage should be small compared to the thermal volt voltage V T. Once we do this we will then get the complete by simply adding the DC and AC results for example, the collector current would be the some of this DC value or the bias value and this AC value. So, the total instantaneous collector current would be the DC value plus the AC value.

And we will assume as we did earlier as well that the coupling capacitors CB and CC these 2 as well as the bypass capacitor CE are large enough. So, that at the signal frequency let us say 1 kilo hertz they can be replaced by short circuits. And that simplified this AC circuit considerably as we saw earlier and will get back to that in the next slide.

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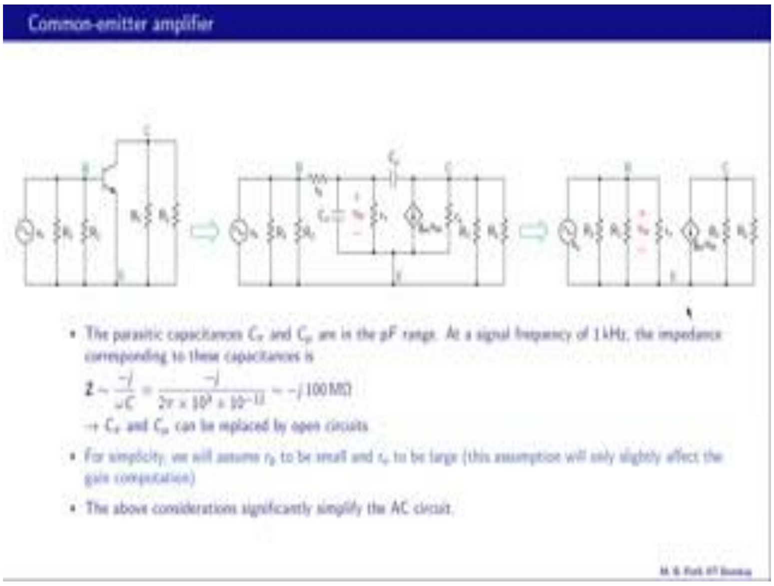

## Common-emitter amplifier

- The parasitic capacitances $C_\pi$ and $C_\mu$ are in the pF range. At a signal frequency of 1 kHz, the impedance corresponding to these capacitances is

  $Z \sim \frac{-j}{\omega C} = \frac{-j}{2\pi \times 10^3 \times 10^{-12}} \sim -j\,100\,\text{M}\Omega$

  → $C_\pi$ and $C_\mu$ can be replaced by open circuits.
- For simplicity, we will assume $r_b$ to be small and $r_o$ to be large (this assumption will only slightly affect the gain computation).
- The above considerations significantly simplify the AC circuit.

So, here is our AC circuit. After replacing the coupling capacitors CB and CC and also the bypass capacitor CE with shot circuit. And now we know how the transistor looks like under small signal conditions and let us replace this transistor with it is small signal model namely all of these. So, then we get this complex looking circuit, now it turns out that the parasitic capacitances the so, called devise parasitic Cpi and Cmu these capacitors. Here they are in the Pico farad range and at a signal frequency of one kilohertz the impedance presented by these capacitors is very large. And what is the impedance minus j over omega C so, minus j over omega 2 pi times 1 kilohertz times C. Let us say one Pico farad range that turns out to be 100 mega ohms rather large resistance as much larger that all of these other resistance values which is which are in the range of kilo ohms.

So, what it means is that this Cpi and Cmu are as good as open circuits because they present such a large impedance at the frequency of interest that is 1 kilohertz or thereabouts. Apart from that for simplicity let us assume that rb is small, this resistance here, and ro is large. Now these are reasonable approximations and if you make this assumption it will only slightly affect our gain computation for the amplifier. So, with all of these considerations, let us see what the AC circuit now looks like. It is significantly signified, and that is what it looks like. So, this capacitor is an open circuit this capacitor is also an open circuit this is 0. So, from the base now we have Rpi going to the emitter that is the common node here. So, from the base we have Rpi going to the emitter that is the common node from the collector, we do not have this it is an open circuit and we do not have ro because that is very large.

So, from the collector we have this voltage controlled current source going to the emitter and in addition of course, we have this RC and R L. So, from the collector we have the voltage controlled current source RC and R L all going to the emitter. So, now, the circuit has become much simpler. And let us now analyze this circuit and calculate the gain for the amplifier. From the AC circuit it should now be clear why this configuration is called the common emitter amplifier. There is a base emitter circuit here, there is a collector emitter circuit here, and as we can see the emitter node is common to both of these circuits. And that is why common emitter amplifier. There are also common base and common collector configurations and they are also useful in some applications.

To summarize we now have the complete AC equivalent circuit for the common emitter amplifier and we are in a position to find the amplifier gain using the equivalent circuit which we will do in the next class, until then goodbye.