Basic Electronics
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Lecture – 23
Bipolar Junction Transistor (continued)

Welcome back to Basic Electronics. We are looked at some basic description of the BJT in the last class. We will now consider a simple BJT circuit, and see how we can obtain the solution that is currents and voltages. We will then see how the BJT can be represented for generalized biased conditions using the Ebers-Moll model. We will get started with the Ebers-Moll model in this class, and see how it can be used to obtain the BJT, I-V characteristics in the next class.

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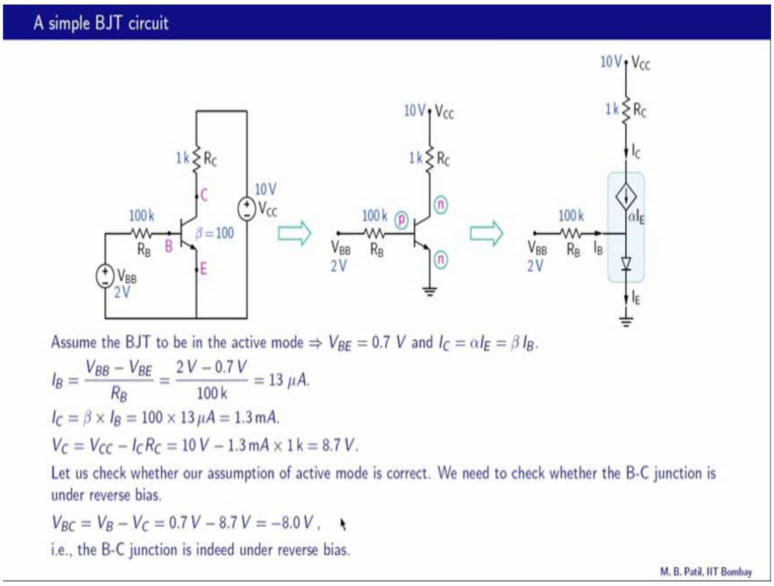

A simple BJT circuit

Assume the BJT to be in the active mode $\Rightarrow V_{BE} = 0.7\ V$ and $I_C = \alpha I_E = \beta I_B$.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{2\,V - 0.7\,V}{100\,\text{k}} = 13\ \mu A.$$

$I_C = \beta \times I_B = 100 \times 13\,\mu A = 1.3\,\text{m}A.$

$V_C = V_{CC} - I_C R_C = 10\,V - 1.3\,\text{m}A \times 1\,\text{k} = 8.7\,V.$

Let us check whether our assumption of active mode is correct. We need to check whether the B-C junction is under reverse bias.

$V_{BC} = V_B - V_C = 0.7\,V - 8.7\,V = -8.0\,V$,

i.e., the B-C junction is indeed under reverse bias.

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Let us begin, let us apply what we have learned so far to this simple BJT circuit. Here is a transistor and it has got a beta of 100. How do we know whether it is a pnp transistor or an npn transistor. First, there is an arrow here that means this node is the emitter, the arrow is coming out of the device so that means, and there is a pn diode over there. So, this node must be p. and that one must be n, and if the emitter is n, the collector is also n-type and so we have npn transistor. Of course, this is all right for the first time, later as we get used to transistor circuits we would not really need to do all this (Refer Time: 02:02) to find out whether it is an npn transistor or pnp transistor. Arrow coming out it is an npn transistor, arrow going in is a pnp transistor. There are 2 voltage sources in this circuit one is called V BB and that is because it is going to the base terminal; and the other voltage source is called V CC and that is because it is going to the collector terminal.

Now, this voltage sources have been shown explicitly. And in electronics, it is a good practice, it is a common practice not to show this voltage sources explicitly, because it is just makes the circuit diagram cumbersome. And therefore, what is done is a reference node or ground is taken such as this node and with respect to that ground we see V BB is 2 volts here, and V CC is 10 volts here, so that is 0 volts. You go up like that you get 2 volts; you go up like that you get 10 volts. Now, for simplicity for clarity in this particular circuit, we will show this npn explicitly, but as we get used to transistor circuits, we do not really need to do that.

Next, we replace the transistor with its equivalent circuits; assuming that the transistor is operating in the active mode. So, let us do that and that is what we get. So, the rest of the circuit remains the same, and the transistor has now been replaced with this rectangle here. And what do we have inside between the base and emitter, we have this diode; and between the base and collector, we have the current controlled current source that we have seen before. And if this current is I E then the collector current is alpha times I E. And now we can proceed and obtain the solution for this circuit.

Let us see how to do that. Since the BJT is assumed to be in the active mode, this diode is forward biased and the voltage top between B and E, B and E is V B E equal to 0.7 volts. And in the active mode we can also say that I C is alpha times I E and that is the same as beta times I B as we have shown earlier. And therefore, if we know this voltage drop we know that this is 2 volts, so 2 minus 0.7 is 1.3 volts. So, 1.3 appears here and 1.3 divided by 100 k gives us the base current, so that is what this equation shows and that turns out to be 13 microamps.

Once we know the base current, we can calculate the collector current, so the collector current is beta times I B that is 100 times 13 microamps or 1.3 milliamps. What about the collector voltage here or here, it is 10 volts minus collector current times R C, this voltage drop here, so 10 volts minus 1.3 milliamps times 1 k that turns out to be 8.7 volts. So, let us get the complete picture. Now, this is 2 volts, this voltage drop is 0.7

volts, but this is at 0. So, this is at 0.7 volts the base and the collector is at 8.7 volts. So, now, we know the voltages at all terminals of the BJT.

Now, let us go back and check whether our assumption of active mode is correct. And what is active mode the base emitter junction is forward biased; and we have already made that assumption; and the base collector junction should be under reverse biased. So, we need to basically check now whether the B-C junction - the base collector junction is ended under reverse bias with the values of voltages that we have obtained. What is V BC V B minus V C, V B is 0.7 volts as we saw before, V C is 8.7 volts, and so the difference between these two is minus 8 volts, so that means the base is at a negative potential compared to the collector. And therefore, this pn junction is under reverse biased. So, that verifies that our assumption of active mode is indeed correct. So, everything is consistent and the solution we have obtained would make sense.

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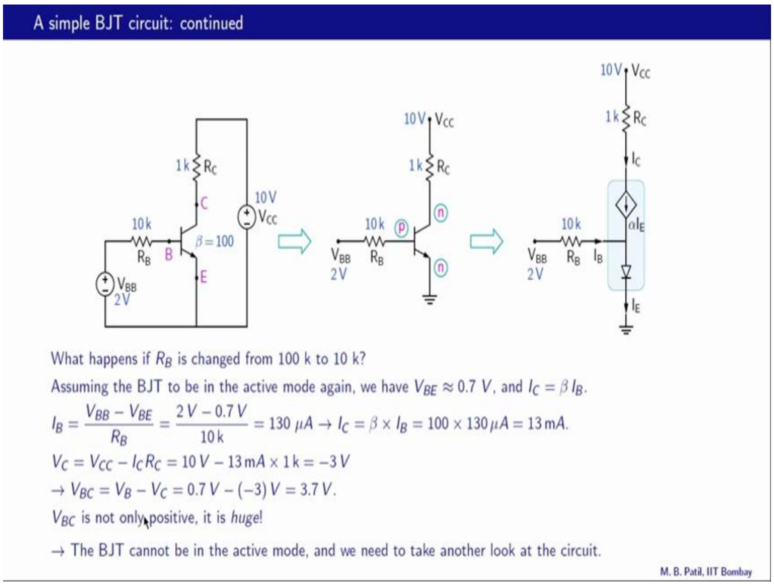

A simple BJT circuit: continued

What happens if R_B is changed from 100 k to 10 k?

Assuming the BJT to be in the active mode again, we have $V_{BE} \approx 0.7\,V$, and $I_C = \beta\, I_B$.

$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{2\,V - 0.7\,V}{10\,k} = 130\,\mu A \rightarrow I_C = \beta \times I_B = 100 \times 130\,\mu A = 13\,mA.$

$V_C = V_{CC} - I_C R_C = 10\,V - 13\,mA \times 1\,k = -3\,V$

$\rightarrow V_{BC} = V_B - V_C = 0.7\,V - (-3)\,V = 3.7\,V.$

V_{BC} is not only positive, it is *huge*!

→ The BJT cannot be in the active mode, and we need to take another look at the circuit.

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Let us now consider the same circuit, but with the slight change. We have changed R B from 100 k to 10 k now. And, now we want to see what the solution is the corrector current as well as the various BJT voltages. So, let us repeat the procedure that we followed in the last slide. First, assume the BJT in the active mode again. So, we have V BE equal to 0.7 volts and I C equal to beta I B, no difference, same as what we saw earlier. I B is of course, different now, because our R B is different I B is V BB 2 volts minus 0.7 divided by 10 k, this was 100 k earlier, now it is 10 k. So, is 2 minus 0.7 1.3

divided by 10 k which turns out to be 130 microamperes. Once we know I B, we can calculate I C that is beta times I B or 100 times 130 microamps, so that happens to be 13 milliamps.

Now, the corrector voltage the voltage at this node is V CC 10 volts minus I C R C. So, 10 minus 13 milliamps times 1 k, it now turns out to be negative minus 3 volts. Does this make sense, let us see. What is V B C then V B minus V C; V B is 0.7 volts because we have assumed this diode to be conducting and V C as we just found is minus 3 volts. So, V B minus V C is 0.7 minus minus 3 are 3.7 volts. So, V B minus V C is 3.7 volts. So, this junction is now under forward bias which is of course, not the condition we required for the active mode. So, something is definitely not right.

So, V B C is first of all its positive and it is huge, no diode is going to tolerate that kind of large voltage, because the current would just be 100 of amperes and that is not possible. So, the solution that we have got is not correct and so what went wrong, what went wrong is our assumption of the BJT being in the active mode was not correct. So, the BJT cannot be in the active mode, and therefore, we need to take a second look at the circuit. So, we will come back to this circuit, after we cover the BJT, I-V characteristics.

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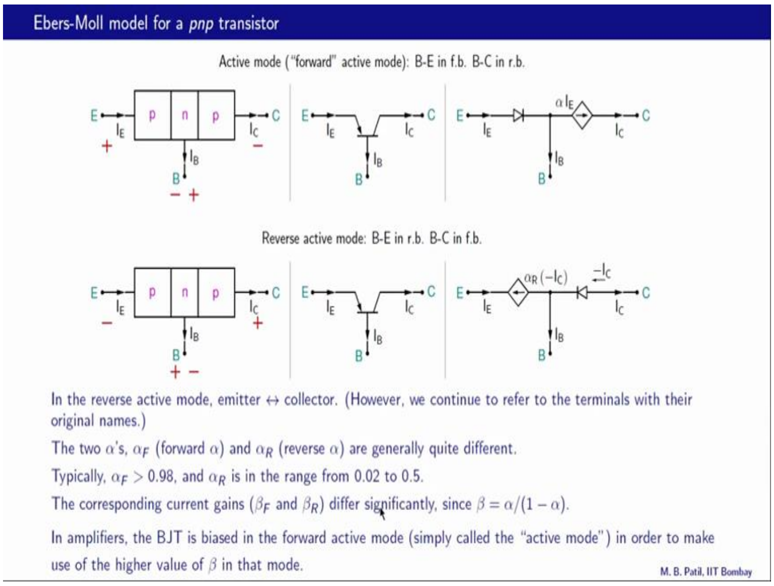

Ebers-Moll model for a *pnp* transistor

Active mode ("forward" active mode): B-E in f.b. B-C in r.b.

Reverse active mode: B-E in r.b. B-C in f.b.

In the reverse active mode, emitter ↔ collector. (However, we continue to refer to the terminals with their original names.)

The two α's, α_F (forward α) and α_R (reverse α) are generally quite different.

Typically, $\alpha_F > 0.98$, and α_R is in the range from 0.02 to 0.5.

The corresponding current gains (β_F and β_R) differ significantly, since $\beta = \alpha/(1-\alpha)$.

In amplifiers, the BJT is biased in the forward active mode (simply called the "active mode") in order to make use of the higher value of β in that mode.

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We have seen so far the active mode of the BJT both pnp and npn. Here is a pnp transistor for example. And what happens in the active mode, the base emitter junction is under forward bias, so that we replace with the diode; and the base collector junction is under reverse bias, and we put a current controlled currents source over there. And if this current is I E that is alpha times I E and alpha is close to 1 little less than 1. Now, if we look at this transistor, we realize that there is a diode there; there is also a diode there. So, there is also a reverse active mode possible and that is shown here. What was that mean that means, this base collector junction is under forward bias and this junction the base emitter junction is under reverse bias, so that is another possibility.

And now what we do is since this is under forward bias, we put a diode there. And if since the base emitter junction is under reverse bias, we put a current controlled currents source there. If this current is minus I C, this current is minus alpha R times that current as showed there. And note that we have continued to use the same terminal names. So, collector here, collector here, all though this terminal is now acting as an emitter, because that is under forward bias.

So, there is an alpha associated with this active mode or more appropriately the forward active mode. And there is also an alpha associated with the reverse active mode, this alpha. And this is called alpha F or very often simply alpha, and this is called alpha R; alpha F is also called forward alpha, alpha R is called the reverse alpha. And they are generally quite different because as we mentioned earlier the base emitter junction and the base collector junction are very different from each other, the doping densities are not symmetric under for these two alphas are generally quite different. Typically alpha F is much closer to 1, for example, it could be greater than 0.98, alpha R is small compared to 1, and it could be as small as 0.02. And as a result, the corresponding current gains beta F corresponding to this alpha F and beta R Corresponding to this alpha R, they also differ very significantly since beta is alpha over 1 minus alpha.

In amplifiers, we do not normally bother about this reverse active mode because the reverse beta is so poor. So, in amplifiers and many other analog applications, the BJT is biased in the forward active mode or it is simply called the active mode, we do not often mention this word forward; and that is done because we want to make use of the higher value of beta in the forward active mode. So, to summarize, the transistor is capable of operating in the reverse active mode. But in most applications, we do not operate the transistor in that mode because the alpha R value is 4, and therefore, the beta R value is 4 and therefore, the perform performance of the circuit if the BJT operates in the reverse active mode would be very poor.

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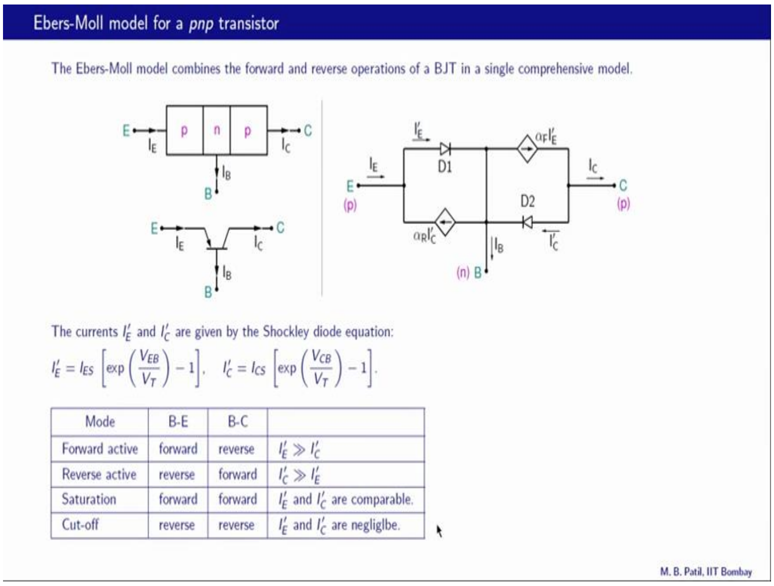

Ebers-Moll model for a *pnp* transistor

The Ebers-Moll model combines the forward and reverse operations of a BJT in a single comprehensive model.

The currents I'_E and I'_C are given by the Shockley diode equation:

$$I'_E = I_{ES}\left[\exp\left(\frac{V_{EB}}{V_T}\right)-1\right],\quad I'_C = I_{CS}\left[\exp\left(\frac{V_{CB}}{V_T}\right)-1\right].$$

Mode	B-E	B-C	
Forward active	forward	reverse	$I'_E \gg I'_C$
Reverse active	reverse	forward	$I'_C \gg I'_E$
Saturation	forward	forward	I'_E and I'_C are comparable.
Cut-off	reverse	reverse	I'_E and I'_C are negliglbe.

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And that brings us to the Ebers-Moll model for a pnp transistor. We will only consider the pnp transistor to begin with; and later, we will see that the Ebers-Moll model for an npn transistor is very, very similar. And once we understand the pnp transistor model it is almost trivial to get the model for the npn transistor all right. Now, before we begin let us look at the direction of these currents once again that is I E, I C and I B. And easy way to remember this direction is to connect these directions with the BJT in the active mode. And what do we in the active mode, we have the emitter based junction forward biased, and the base connector junction reverse biased.

Now, if this junction is forward biased, then the current that will flow would be in that direction and that is the same direction as the emitter current here, here as well as here. The collector current essentially is in the same direction as the emitter current. So, if the emitter current is like that the collector current is also like that. And the base current is in the same direction as the collector current; if the collector current is coming out of the device then the base current is also shown as coming out of the device.

Another way to look at it is in the active mode all these currents are positive; and that will happen if the base current is shown to be coming out of the device. Let us see why. As we have seen earlier I C is alpha times I E in the active mode and alpha is slightly smaller than 1, therefore I E minus I C is a positive current and that essentially comes out as the base current. So, these currents here I E, I B and I C are reproduced in this figure; I E, I B and I C in the same direction as in the first figure.

And now we come to the Ebers-Moll model. The top branch here corresponds to the active mode and the bottom branch corresponds to the reverse active mode. And let us consider the active mode first. In the active mode, the base emitter junction is under forward bias and base collector junction is under reverse bias. And in that situation, D 1 will conduct and D 2 will not conduct. So, this current is very, very small. So, this branch is as good as an open circuit; and since this current depends on I C prime, this is also an upper circuit. And we are left with the diode here and the dependent source here. And in that case, I E and I E prime will be equal; I C and alpha F or alpha times I E prime will also be equal and that is exactly the model we have considered for a BJT in the active mode.

Similarly, in the reverse active mode, the base corrector junction is under forward bias and the base emitter junction is under reverse bias. And therefore, this current now will be negligibly small, and therefore, the D 1 branch as well as this current control currents source would be open circuits. And now we are left with D 2, and this dependent source. And now I C is minus I C prime, I E is minus alpha R times I C prime, so that accounts for the forward active mode or simply the active mode as well as the reverse active mode. Apart from that we have other two situations; one in which both of these diodes are under forward bias; and another in which both of this diodes are under reverse bias. Now, the nice this about Ebers-Moll model is that it can be used for all of these modes of operations as we will see.

Next, let us look at what I E prime and I C prime are, these currents are given by the Shockley equation. For D 1, we need to take V, E, B as the diode voltage; and for D 2, we have to take V C D as a diode voltage. And when we do that we get these equations I E prime is I E S this is the reverse saturation current for D 1; and it has got this subscript E because that is close to the emitter, S is the reverse saturation. So, I E S times exponential V E B by V T minus 1. So, it is exactly the same as the diode equation we have seen before except V E now V E B. This currents I E S and I C S are very small, a picoampere or even smaller. And in normal operation, this small current would get multiplied by this large exponential factor, and therefore we can get reasonable currents.

So, now we have the complete model. Let us say we know V E, V B and V C - the three terminal voltages, and then we can calculate V E B as well as V C B. Once we know those voltages we can calculate I E prime; this is just a number which is known for a given transistor, V T is the thermal voltage about 25 milli volts at room temperature. So, all of these things are known as soon as we know the terminal voltages. So, we can calculate I E prime as well as I C prime. So, we have this current, that current. If we know this current, we know this current as well because alpha F is also known. If we know I C prime we know this current as well and so we know all of these four currents and we can then write a K cell at the base node to obtain I B.

Here are the various modes in which the transistor can operate in. And there are four modes, because we have two junctions each one can be forward biased or reverse biased, so that gives us more combinations. We have already seen the forward active mode, we have in fact, also seen circuit example of this mode. In the forward active modes, simply called in the active mode very often; the base emitter junction is forward biased, base collector junction is reverse biased. And because of that I E prime this diode current is much, much larger than I C prime. For all practical purposes, we can say that I C prime is 0 in this case.

Then there is the opposite case the reverse active mode in which the base emitter junction is reverse biased, and base collector junction is forward biased. And in this case just the opposite happens. This current is non-zero and I E prime is 0, because D 1 is under reverse biased. And these are the other two modes we have not seen so far there is a mode called saturation in that mode both of these junctions are under forward biased. So, the base emitter junction is under forward biased, base collector junction is also under forward biased, and because of that both I E prime and I C prime are now substantial and they may even be comparable.

In the fourth mode - the cut off mode, both of these junctions are under reverse biased, I E prime is 0, I C prime is 0, this current 0, this current 0, essentially all currents are zero and the transistor looks like an open circuit from any of these terminals. So, that is the cut off mode. And as we said the Ebers-Moll model can be used for any of these modes and that is the many attractive feature of this model, and it is therefore, commonly used. In circuit simulators, there is another model which is a little more advanced, but essentially the idea is similar that the model describes all of these modes in the nice comprehensive manner that is called the (Refer Time: 25:54) model. For our purpose is the Ebers-Moll model is definitely adequate and we will see the results that we get from this model.

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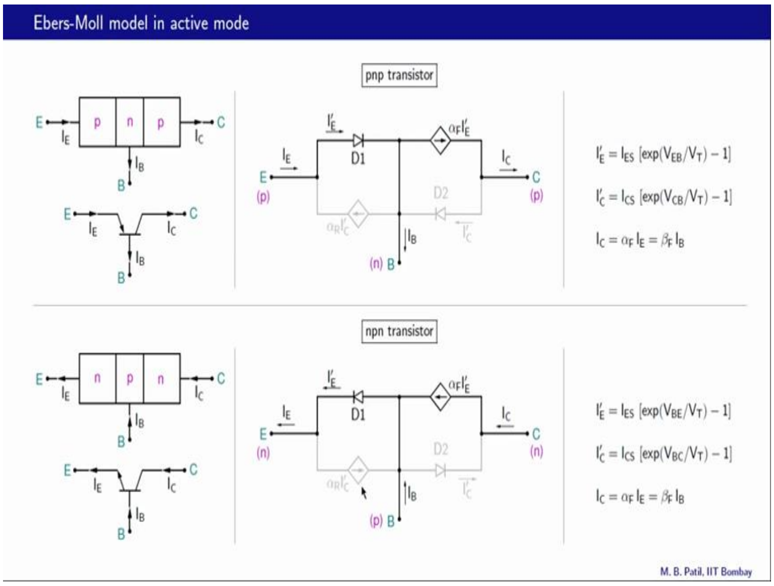

Ebers-Moll model in active mode

pnp transistor

$I'_E = I_{ES}\,[\exp(V_{EB}/V_T) - 1]$

$I'_C = I_{CS}\,[\exp(V_{CB}/V_T) - 1]$

$I_C = \alpha_F\, I_E = \beta_F\, I_B$

npn transistor

$I'_E = I_{ES}\,[\exp(V_{BE}/V_T) - 1]$

$I'_C = I_{CS}\,[\exp(V_{BC}/V_T) - 1]$

$I_C = \alpha_F\, I_E = \beta_F\, I_B$

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Here is the summary of what we have said about the Ebers-Moll model; and we also show the npn Ebers-Moll model in this figure. For the pnp transistor, the emitter current is into the device; the collector current is in the same direction as the emitter current; and the base current is out of the device. And if we write KCL, we get I equal to I B plus I C with all plus signs. In this case, we talk about V E B as the forward bias for D 1, and therefore that is the voltage that enters the equation for I E prime. For the other diode for D 2, we talk about V C B as the diode voltage and that is voltage that enters the equation for I C prime.

For the npn transistor, we show I E as flowing out of the device and is easy to imagine why it is out of the device under active mode. We have a p n diode there under forward bias and that forward biased diode is going to allow current only in that direction, so that is the direction of I E. I C is in the same direction as I E and I B is going into the device; And once again if you write KCL we will get I E equal to I B plus I C with all plus signs. The Ebers-model for the npn transistor is here; and as we see it is very similar to the case for the pnp transistor except now we have this polarity of D 1 and D 2 reversed because earlier we had pn here, now we have pn like that. So, therefore, the polarity of D 1 is reversed as well as the polarity of D 2. The I E prime current is now marked in the other direction because we expect this current now to be positive when the when D 1 is under forward bias. The current controlled current source here is also in the opposite direction, essentially the same direction as I E prime. So, this is still given by alpha F times I E prime.

Similarly, I C prime is in that direction, because that is the direction, in which the current flip flow f D 2 is under forward bias. And the other current controlled current source also is in the same direction as I C prime. And what about the base current, the base current can be obtained once again by writing the KCL equation at this node; these two nodes of course, are the same and so all these two. I E prime is now given by this equation is very similar to the pnp Ebers-Moll equation, except we have V B E now, and the reason is simple because this diode is forward biased, if V B E is positive that is why we are V B E here. Similarly, in the I C prime expression, we have V B C here and not V C B.

So, things are definitely very analogous in these two cases; and we do not really need to remember any of these. We can actually just sit down and draw these models on paper and that are what they stop is saying. So, stop watching the video, take a break, take your pen and paper and draw these Ebers-Moll models for the pnp transistor as well as for the npn transistor. Once you are finished with that come back, and check if you got everything right and then we will proceed further.

Let us now look at the Ebers-Moll model in the active mode, and we have commented on this earlier, but let just put it down once again because it is so important. And we will do that for both pnp and npn transistors. In the pnp transistor, what is the meaning of active mode that means, D 1 is forward biased and D 2 is reverse biased. So, therefore, this current is very small, and we can treat that as an open circuit and that is why it appears in light color, if this I C prime is small alpha R times I C prime is also small, and therefore, that is also an open circuit.

Then the Ebers-Moll models based on to D 1 and this current controlled current source and that is exactly what we considered earlier; same thing for the npn transistor - D 1 is under forward biased, D 2 is under reverse biased, so this current is negligibly small, so is this current. And therefore, we are left with d one and this current controlled current source. And now in both of these cases, this I E becomes equal to I E prime; and I C becomes equal to alpha times I E prime, and that is the same thing here except for the directions of the current. I E and I E prime are the same and I C and alpha I E prime or alpha I E are the same.

So, this slide only shows that Ebers-Moll model does reduce to the BJT model in the active mode that we considered earlier. So, it is special case of the Ebers-Moll model. And whenever we come across a BJT the active mode, we can conclude that the base emitter diode has about 0.7 volts across it is conducting in the forward direction. And the collector current is alpha f times I E alpha f is often just called alpha, and as you have seen before that is the same as the beta times I B. And these relationships hold both for the pnp transistor and npn transistor without any negative signs provided we denote our currents as shown here.

To conclude, we looked at the simple BJT circuit in this class, in which the transistor operates in the active mode. We found that changing one of the resistance values gives results which are not consistent with the assumption of active mode. Clearly, in this case the BJT is operating in some other mode; to handle situations like this we need a BJT model which can be used in all modes of operation. The Ebers-Moll model is one such model, it is relatively easy to understand and is also reasonably accurate. Using the Ebers-Moll model, we can describe the BJT behavior completely as we will do in the next class. So, see you next time.