Analog Electronic Circuits
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Lecture - 09
Revisiting BJT Characteristic (Contd.)

So, dear students, we will come back to this Analog Electronic Circuits course and as you may be knowing that we are Revisiting BJT Characteristic which is one of the prerequisite items. And we already have seen the working principle of the BJT, and today we are going to the second part of it and particularly how we use the equation to analyze the circuit.

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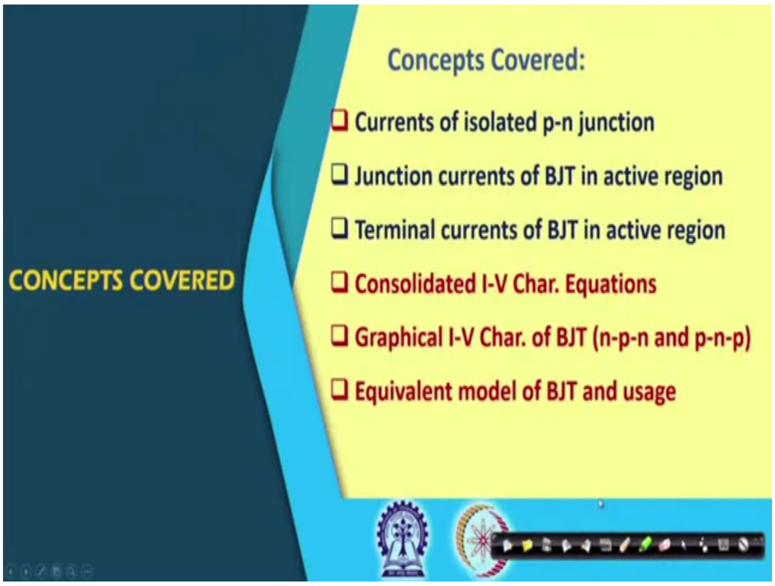

CONCEPTS COVERED

Concepts Covered:

- ☐ Currents of isolated p-n junction
- ☐ Junction currents of BJT in active region
- ☐ Terminal currents of BJT in active region
- ☐ Consolidated I-V Char. Equations
- ☐ Graphical I-V Char. of BJT (n-p-n and p-n-p)
- ☐ Equivalent model of BJT and usage

So, these are the concepts we have already have covered the blue colored first 3 items we already have covered and today we are going to the I-V characteristic and how we use the I-V characteristic to analyze say simple BJT circuits. And, also we look into the difference between I-V characteristic of p-n-p transistor with respect to n-p-n transistor because the working principle so far we have dealt with in detail about a n-p-n BJT transistor.

So, we do not like to repeat for p-n-p transistor; however, you can deploy it for p-n-p transistor. Then we are here we are primarily focusing on what is the basic difference between the two device characteristic and then we are going for the equivalent model of the BJT. Particularly, what is the equivalent circuit we will be using; instead of equation normally we prefer to deal with equivalent circuit. And, then we will be covering some of the maybe two numerical problems related to that.

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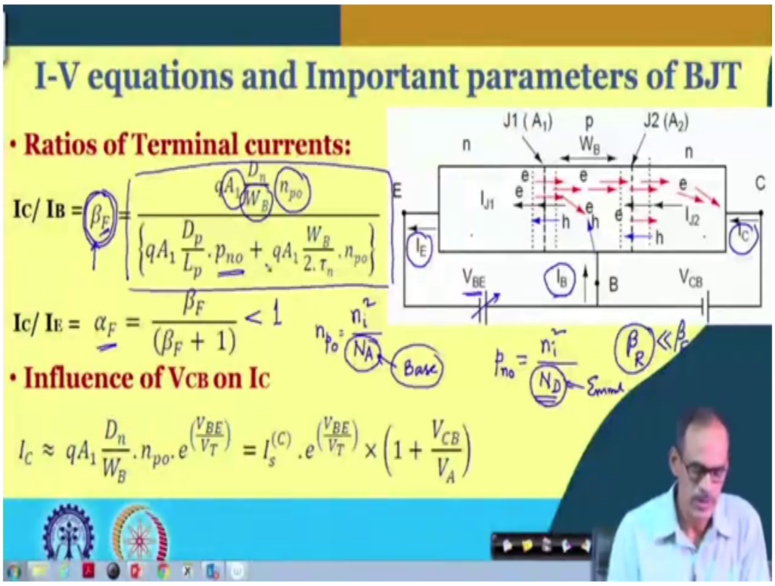

I-V equations and Important parameters of BJT

- Ratios of Terminal currents:

$$I_C/I_B = \beta_F = \frac{qA_1 \frac{D_n}{W_B} n_{po}}{\left\{qA_1 \frac{D_p}{L_p} \cdot p_{no} + qA_1 \frac{W_B}{2 \cdot \tau_n} \cdot n_{po}\right\}}$$

$$I_C/I_E = \alpha_F = \frac{\beta_F}{(\beta_F + 1)} < 1$$

- Influence of V_{CB} on I_C

$$I_C \approx qA_1 \frac{D_n}{W_B} \cdot n_{po} \cdot e^{\left(\frac{V_{BE}}{V_T}\right)} = I_s^{(C)} \cdot e^{\left(\frac{V_{BE}}{V_T}\right)} \times \left(1 + \frac{V_{CB}}{V_A}\right)$$

$$n_{po} = \frac{n_i^2}{N_A} \leftarrow \text{Base}$$

$$p_{no} = \frac{n_i^2}{N_D} \leftarrow \text{Emitter}$$

$$\beta_R \ll \beta_F$$

So, let me go to these slides where last we have concluded, yeah. So, this is the slide where we have concluded in the previous part of this module. So, what we have discussed here it is the biasing we already have discussed and then we also have said that how do we vary the junction potential. Particularly, the V BE and then when you observe the base current and then when you observe the emitter current and when you observe the collector current what are their dependences are represented by primarily these two equations. In fact, all these currents, all the 3 currents they are exponential function of the base to emitter junction voltage.

And, so if we take the ratio of the collector current divided by the base current the exponential part do get cancelled out and then whatever the constant or the remaining parts we do have that comes as an important parameter called the beta of the transistor or to be more precise it is referred as base current to collector current gain. And, as you can see in this expression that this is primarily it is function of a different device parameter internal parameter, namely the base weight, then base to emitter junction cross sectional area and so and so.

In fact, we can also see that it is function of the n p naught which is the minority carrier concentration in the base region. So, likewise we also have minority carrier concentration in the emitter region. So, namely n p 0 is nothing but n i square intrinsic carrier concentration divided by N A the acceptor carrier concentration in the base. So, this is corresponding to the base region. So, likewise the p n naught the minority carrier concentration deep into the emitter region; so, that is equal to n i square divided by N donors concentration in the emitter region.

So, whatever it is. Here you can say that if we really are looking for a device which is working as a good amplifier. We like to have this base to collector current gain beta should be as high as possible. And this equation reflects that how we can make this beta to be high, one is the base weight and of course, another is the doping concentration in the base region, and then also the doping concentration in the emitter region. So, those are the detailed parameters related to the device.

As a circuit designer what will be looking for it is that if the device is given to us we will be looking for a decent value of this beta F forward direction current gain. And, also we have just given a hint that this F stands for forward direction, namely if the emitter it is really used as an emitter, collector it is really used as a collector and of the if the device it is in active region then whatever the base to collector current gain we do get we call it is beta F.

On the other hand, in case if we pretend the collector region or the collector terminal as emitter and emitter terminal as current of course, then corresponding N D instead of this region emitter region we have to consider N D of the collector region and its corresponding concentration it is quite different from emitter. So, as a result whatever the current gain in that case we will be getting that is also called beta, but you may say that it is in the reverse direction that may be much smaller than in the forward direction beta.

So, while we will be using the device for our circuit, we should understand that the emitter really should be used as an emitter and likewise the collector. Now, we also have another parameter called alpha F which is the emitter to collector current gain. I should not say normal it will be gain, but it is typically as you can see from this expression if the beta F it is very high compared to 1, it may be going approximately 1 though it will be slightly less than 1.

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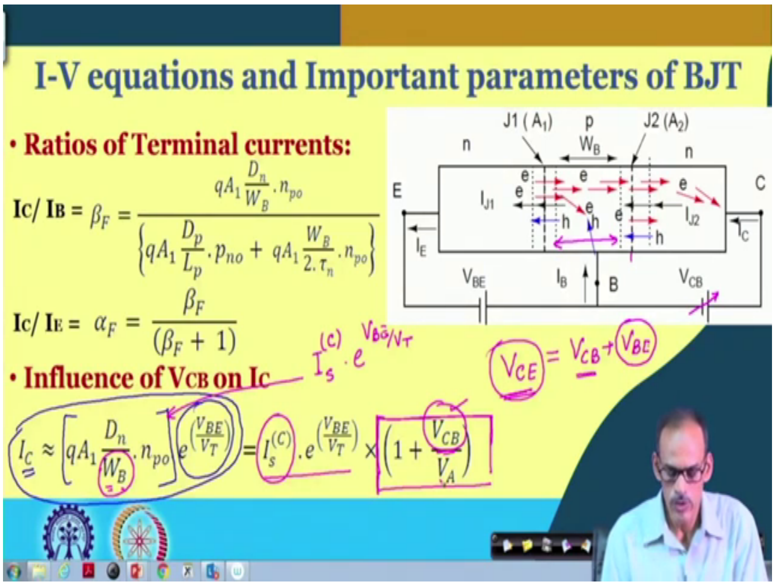

I-V equations and Important parameters of BJT

- **Ratios of Terminal currents:**

$$Ic/ IB = \beta_F = \frac{qA_1 \frac{D_n}{W_B}.n_{po}}{\left\{qA_1 \frac{D_p}{L_p}.p_{no} + qA_1 \frac{W_B}{2.\tau_n}.n_{po}\right\}}$$

$$Ic/ IE = \alpha_F = \frac{\beta_F}{(\beta_F + 1)}$$

- **Influence of VCB on Ic**

$$I_s^{(c)} \cdot e^{V_{BE}/V_T}$$

$$V_{CE} = V_{CB} + V_{BE}$$

$$I_C \approx \left[qA_1 \frac{D_n}{W_B}.n_{po}\right] e^{\left(\frac{V_{BE}}{V_T}\right)} = I_s^{(C)}.e^{\left(\frac{V_{BE}}{V_T}\right)} \times \boxed{\left(1 + \frac{V_{CB}}{V_A}\right)}$$

So, as a device user in our circuit we may not be really dealing with tuning these parameters rather we will be assuming that these parameters are given to us. So, as a circuit designer in that case we will be focusing on the current to voltage characteristic relationship, namely I C as function of the base to emitter voltage through this exponential function and rest of the things this portion we may assume it is constant.

So, say for example, we may consider since this equation current as function of V BE, it is having exponential dependency and it is similar to forward direction diode or forward biased diode, and in that case this whole part it may be considered as reverse saturation current. So, we may use this whole factor as I S and probably you can use I S for the collector terminal into e to the power V BE divided by V T thermal equivalent voltage.

So, it, so it basically this is this is what we are getting here that the main dependency of the collector current as function of V BE and also you may be aware that if we if we change this V CB collector to base voltage. So, it is expected that the second junction it is also getting more and more reverse bias, particularly if you increase it and as a result the depletion region around the assumption increases. So, naturally that decreases the effective base width.

So, if this base width is getting decreased, so we can say that this base width if it is function of V CB. So, naturally this part it is having some weak dependency. So, typically instead of really modeling this W B as function of V CB since this dependence is very weak it is modeled as linear function of V CB and it is considered as additional factor and this part we do consider it is really constant.

So, I should say if I consider W B it is remaining constant, then only we can get the expression of I S of the collector. But in case if we really want to capture the effect of V CB on W B instead of really looking into how much the change it is happening we like to capture that dependency as separate factor like this one plus V CB.

Further to that instead of for circuit convenience instead of considering this is function of V CB we prefer to consider it is V CE because V CE of course, it is not same as V CB which is V CB plus V BE. And all practical purposes, if we change this V CB or V CE this part it is almost remaining constant quote and unquote constant. So, we can say variation in V CB, it can be well approximated by variation in V CE and invariably in our normal characteristic equation instead of using V CB we use V CE. So, that may require additional adjustments, but that can be ignored.

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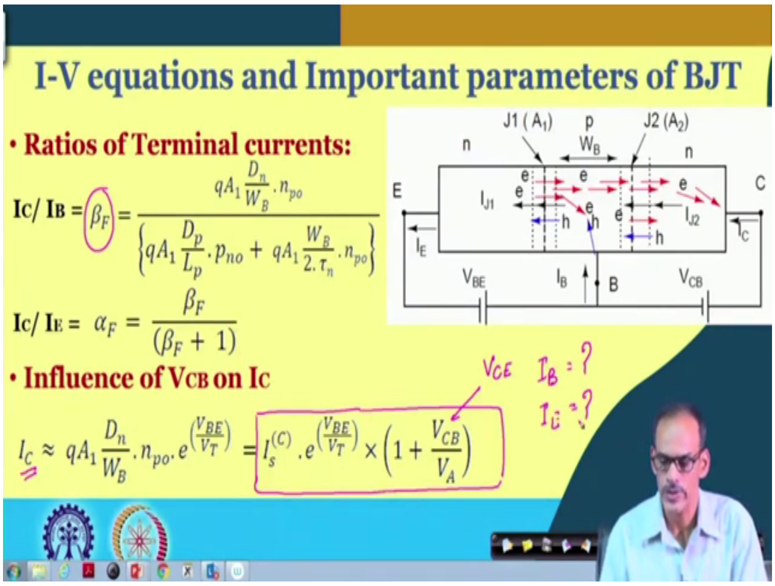

I-V equations and Important parameters of BJT

- **Ratios of Terminal currents:**

$$Ic/\,IB = \boxed{\beta_F} = \frac{qA_1 \frac{D_n}{W_B} . n_{po}}{\left\{ qA_1 \frac{D_p}{L_p} . p_{no} + qA_1 \frac{W_B}{2.\tau_n} . n_{po} \right\}}$$

$$Ic/\,IE = \alpha_F = \frac{\beta_F}{(\beta_F + 1)}$$

- **Influence of VCB on Ic**

$$I_C \approx qA_1 \frac{D_n}{W_B} . n_{po} . e^{\left(\frac{V_{BE}}{V_T}\right)} = \boxed{I_s^{(C)} . e^{\left(\frac{V_{BE}}{V_T}\right)} \times \left(1 + \frac{V_{CB}}{V_A}\right)}$$

V_{CE}

$I_B = ?$

$I_E = ?$

So, end of it what we are getting it is collector current as function of the V BE through this exponential function and it is having a constant and also it is having linear dependency on either you can see V CB or V CE. On the other hand, using this equation this expression of the collector current and using the factor beta F you can find the expression of I B, you can also find the expression of I E. So, that is what we are expecting for circuit analysis, so that these equations you need to be given to us to go for further analysis of a circuit containing BJT.

So, let us move little more detail or rather let us move away from the device operations and detail equation of the devices and whatever the end of it, so whatever the equation we have obtained let we go with that into the circuit, particularly a circuit where you do have the BJT.

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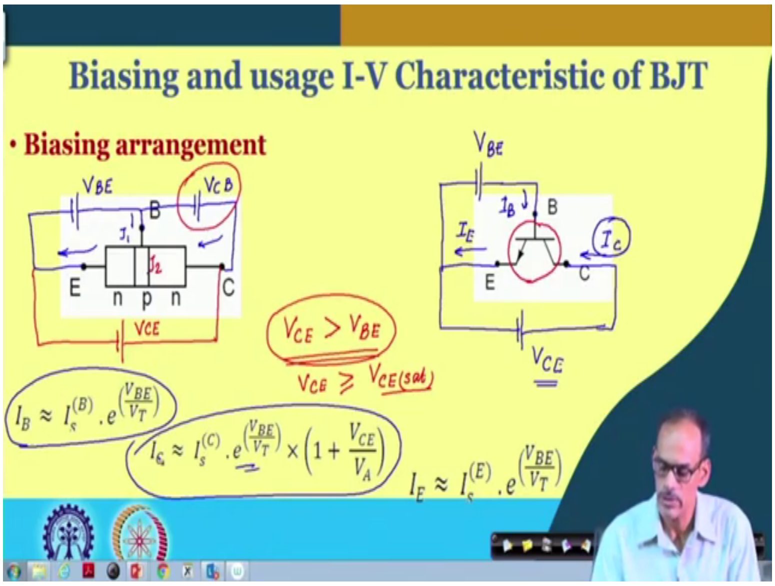

Biasing and usage I-V Characteristic of BJT

- **Biasing arrangement**

$V_{CE} > V_{BE}$

$V_{CE} \geq V_{CE(sat)}$

$$I_B \approx I_s^{(B)} . e^{\left(\frac{V_{BE}}{V_T}\right)}$$

$$I_C \approx I_s^{(C)} . e^{\left(\frac{V_{BE}}{V_T}\right)} \times \left(1 + \frac{V_{CE}}{V_A}\right)$$

$$I_E \approx I_s^{(E)} . e^{\left(\frac{V_{BE}}{V_T}\right)}$$

So, here again we are coming back to the little bit towards the biasing side, but if you see that we do have n-p-n transistor. And, then we do have the two junctions of this transistor base emitter junction we like to make it forward biased for active region of operation of the device or to be more precise we like to keep the junction one to be forward biased.

So, J 1 it is forward biased by this voltage, base to emitter voltage. And this junction it may be reverse bias the second junction by V CB. And then of course, there will it is expected that there will be a current flow this terminal current, the emitter terminal current and the collector terminal current. And, the dependency of those currents you already have said that they are having exponential dependency which is given here and then collector current is having exponential dependency in addition to that some linear part depends on the these junction bias.

So, likewise and what you also say that instead of using the bias here we may prefer to say that it will bias the other junction by applying voltage with respect to emitter and let me call this is V CE. So, if this V CE it is sufficiently high then we can say for a given value of V BE, it is the second junction it is getting reverse bias under this condition. So, strictly speaking to get the reverse bias condition for the second junction this is the condition, but normally for practical purposes even if this junction it is slightly getting forward biased still the device remains in quote and unquote in active region of operation.

And, instead of strictly following this condition we may say that as long as V CE it is a higher than some voltage which may be even say smaller than V BE on we call it is V CE sat. We may discuss this why we call it a sat, but as long as this V CE it is higher than some voltage then we can say that is the second junction all practical purposes it is though it is it may get weakly forward biased, but still these equations of the currents remains valid.

So, instead of in our circuit instead of using this view we may prefer to use the symbol of the device. So, here we do have the symbol of the BJT n-p-n transistor, and its corresponding bias as you said that we do have V BE and then we do have the V CE. So, so we are biasing the circuit like this. So, we do have the V CE here and then V BE here, and then we do have the base current entering into the base of the transistor.

Collector current enter into the device through this collector terminal and then the emitter current it is departing the device through this emitter terminal. And, this is what the also the actual direction of the current flow and the actual the polarity of the positive currents of the collector and base terminal and emitter terminal currents and this is also the corresponding positive polarity of the corresponding terminal and the voltages.

In case, if we have this V CE negative which means that this side it is lower than the emitter side. So, that is how we do this kind of biasing arrangement for the n-p-n transistor. And then further little going little detail of for the BJT circuit let me see what is the next thing we do have if we apply that bias what we have the I-V characteristic particularly graphical representation.

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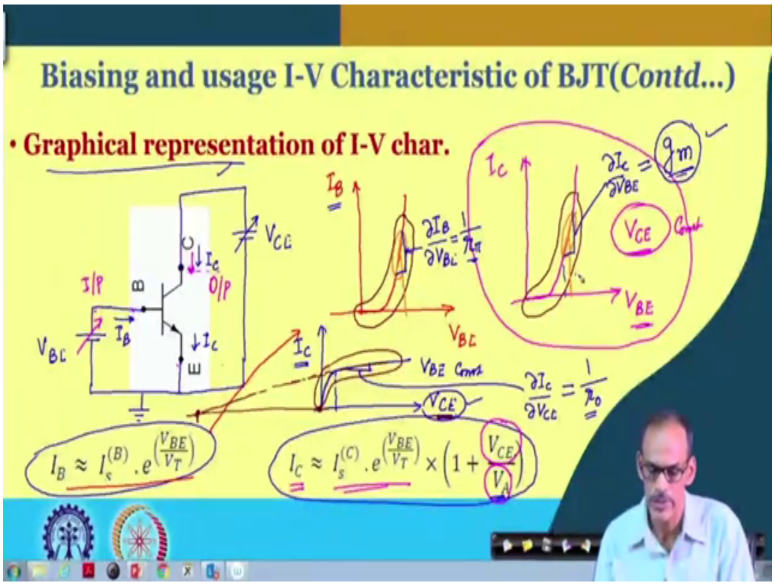

Biasing and usage I-V Characteristic of BJT(*Contd...*)

- **Graphical representation of I-V char.**

$I_B \approx I_s^{(B)} . e^{\left(\frac{V_{BE}}{V_T}\right)}$

$I_C \approx I_s^{(C)} . e^{\left(\frac{V_{BE}}{V_T}\right)} \times \left(1 + \frac{V_{CE}}{V_A}\right)$

Now, we have oriented the device differently. So, we do have the base we are taking towards the left indicating that probably this will be one of the input terminal. And emitter we are to taking down, so we may be assuming that lowest potential of the circuit may be connected to this emitter terminal or at least we can say emitter should be at lower potential than the base. On the other hand, collector terminal we like to keep at higher potential.

So, we simply just reoriented the device for our convenience assuming that we will be having probably at this point we will be having higher potential and we call this is V CE, we call this is V BE and this is the base current, this is the collector current, and this is the emitter current.

Now, their expressions are given here. Of course, these equations are very fundamental equation we have to again and again revisit, but it is also it is important to see that how intuitively we can make use of these equations and to be more precise what may be the graphical representation of this I-V characteristics. So, that is what we are going to focus now.

So, if you are considering say the first equation the I B versus V BE as this equation suggests that it is similar to the diode current in the forward biased condition. So, this will be having exponential behavior. So, this is the equation is getting represented graphically. So, likewise, if you are also plotting the collector current as function of the V BE, so it may be noted that right now we are concentrating the dependency of the I C current as on V BE and as you can see that this part is also exponential.

So, the nature of the two curves are essentially I should say quote and unquote identical. Assuming, V CE it is sufficiently high and we assume that this is remaining constant, so quote and unquote constant. In fact, if even if say this V CE it is changing since this part it is very small and in other words you can say that this early voltage is very high making this part is practically approximately one, so even if V CE is changing this exponential nature of the collector current on V BE it is still valid.

So, this part of course, you can say it looks like it is a forward direction diode or rather forward bias diode, but on the other hand if you see this characteristic it is kind of a different in nature because we are observing the current at the collector terminal while we are changing the voltage from base to emitter. So, in other words you can say that is like a trans-characteristic. So, we are changing the voltage from base to emitter while you are observing the corresponding effect at the other terminal and down the line we will see that for many application we consider this is the input.

So, we can say that this is the input port from base to emitter and at the collector we are observing the corresponding effect and this will be treated as the output. So, we can say that input to output port trans-characteristic it is primarily represented by this one. In fact, this is very vital for to understand the amplifier where we feed a signal at the input port and we are observing that corresponding effect at the output port. In this case of course, it is voltage to current later on we will also see that voltage to voltage relationship. So, whatever it is this is of course, it is trans-characteristic.

And you can also see that the collector current is function of V CE though it is a weak function, but still it is having dependency. So, how do you represent that? So, if we plot say I C as function of V CE keeping V BE constant. So, which means that we are keeping this voltage constant we are simply varying this one and then we are observing the collector current. So, if I assume that this second junction namely collector base to collector junction if it is remaining reverse bias.

So, we can see that through this equation or this equation represents that dependence is very weak. So, depending on the value of this V A, the parameter V A there will be slight change; however, if the V CE it is sufficiently low and if this junction it is getting forward bias there will be bend of this current. In fact, you can you can say that if this voltage it is this voltage it is 0 of course, it will go to the origin. So, there will be a big dependency of the collector current on V CE only when this junction it is getting forward biased, but till that point as long as it is reverse biased we can say that this current is fairly quote and unquote independent of the V CE voltage. So, of course, depending on this value of this V A we can say it is independent.

Now, what is the significance of this V A and the slope of this line is the following. So, if you extrapolate this I-V characteristic wherever it intersects the V CE axis, then whatever the value we will get that voltage it is minus V A. So, this is this that represents that at V CE equals to minus V A this part it becomes 0 and hence the corresponding current the extended current it is becoming 0. So, that is the significance. In other words, you can say that higher the value of this point then in other words if this point it is far away from the origin slope of this line it is less.

Now, if you see this the graphical interpretation of I-V characteristic, they do have other meaning also particularly what presently whatever the characteristic we have plotted we have changed this V CE and V BE quite a large extent pushing the device into heavily you know saturated portion. Namely, we are we are seeing that the highly non-linear effect from here to here. So, likewise here also we can see highly non-linear effect. Here also if you push the device into this region beyond the active region of course, we can see the highly non-linear part.

But whenever we will be focusing on amplifier we maybe keeping our you know signal will restricted within narrow range maybe somewhere here and probably around that whatever the slope of the characteristic that may be important. So, likewise here also if we keep the V BE the current my having linear dependency on that V BE that can be represented by the slope of this characteristic line same thing for this also.

So, as we will be using this circuit particularly BJT as an amplifier particularly for analog circuit, so we like to prefer to translate the non-linear characteristic or rather restricting this non-linear characteristic within a certain range ensuring that linear behavior of input to output relationship it is getting maintained. And, we will also be seeing that apart from this large signal behavior what is important thing is that slope of this line is very important. Slope of this line it is very important.

So, whenever we will be going to the small signal model or equivalent small signal model as you have discussed for diode the slope of this line it is important and slope of this line equation wise it is change in I B with respect to V BE. So, likewise here the slope it is change in I C with respect to V BE and so likewise here if you see the corresponding slope here that, can that is also of course, change in I C, but with respect to V CE.

And each of these slopes they do have their own interpretation and since we will be dealing with this slopes more frequently. So, it is better to give a different name and give different you know you know parameter or symbol to represent this one. Say for example, this is this is getting represented by g m, g m stands for trans-conductance, m stands for mutual input to output port that is why it is trans, g represents conductance. So, input port to output, so input voltage to output current relationship it is getting represented by this slope or this parameter called g m. So, trans-conductance of the device it is for the g m.

So, likewise, this slope it is having some meaning. In fact, if you see that it is expressing the relationship between the input terminal current to input port voltage. So, you may say that this is nothing, but 1 by input port resistance, it is 1 by r pi. So, likewise if you see the I C I C versus V C characteristic curve, so this slope it is also having interpretation as the output port conductance or one by r o, r o is the output port resistance.

Of course, this r o it is small signal resistance r pi it is small signal input port resistance and g m it is trans-conductance keep keeping in mind that we are restricting the signal within certain range. So, that the linearity model it is valid. So, that is the graphical representation of this I-V characteristic equation.

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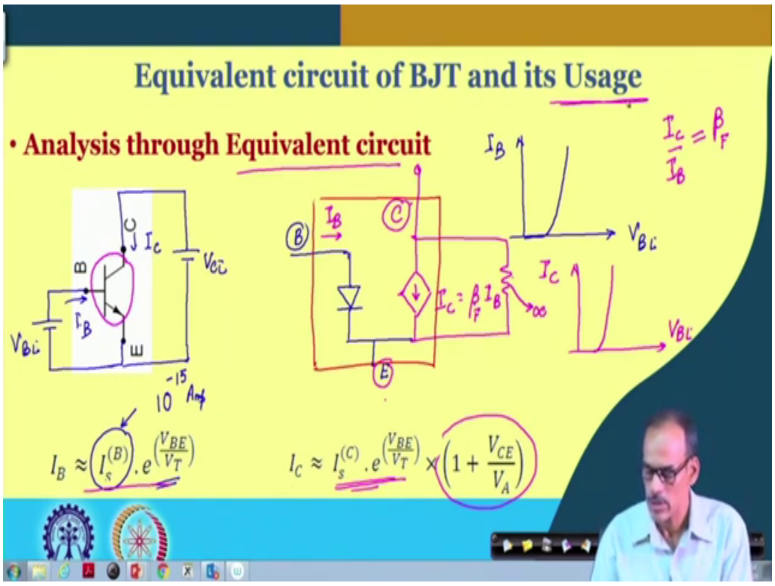

Equivalent circuit of BJT and its Usage

- Analysis through Equivalent circuit

$$I_B \approx I_s^{(B)} . e^{\left(\frac{V_{BE}}{V_T}\right)}$$

$$I_C \approx I_s^{(C)} . e^{\left(\frac{V_{BE}}{V_T}\right)} \times \left(1 + \frac{V_{CE}}{V_A}\right)$$

So, if we see how do we then in actual circuit how do we use this equation. So, that is probably very important for the circuit analysis. So, I again I am going to use the same kind of bias here probably we can keep the bias V B here. And then we can have the V CE and our main interest is to find what will be the corresponding current here, here and so and so.

Now, what we will be doing is that since we already have seen that the I B. So, I B versus V B characteristic curve it is having similar kind of behavior of a diode. So, I B versus V B it is it looks like it is a diode. So, from base to emitter terminal probably its behavior can be represented by a diode. So, you may say that this is our emitter terminal and this is the base terminal and in between we do have a diode.

So, whatever the diode its corresponding reverse saturation current is this one it typically it is a very small compared to normal diode, but still you may say that the diode can represent its behavior. Though this value of this one it will be in the order of maybe 10 to the power may be minus 15 ampere in comparison with diode, if I say that for a typical diode normal signal diode this will be 10 to the power minus 13 ampere so, but then the exponential relationship it is getting maintained.

Now, next thing is that ok, this base to emitter port it is relatively simpler, but however, the other port the collector to emitter port where we do have I C. I C it is as a function of e rather it is strong function of V BE that is what we see it and it is having exponential dependency. So, of course, this is a trans-relationship. So, directly we cannot put the diode, but then we also know that I C divided by I B it is quote and unquote remains constant. So, whatever beta F we do have.

So, probably this characteristic can be represented by say current control current source. So, you may say that this is current control, current source and this current it is getting controlled by I B, so we may say that this I C equals to beta F into I B. In fact, this part it is well captured by this relationship.

Now, in case, if you also want to represent this part probably the dependency of the total current to collector current that can be also captured by this one, so you may put some additional conducting path from collector to collector to emitter. Typically, since this part is very small we do ignore this part, we assume that this resistance is quote and unquote it is going to infinite and we may ignore. So, remaining things it fairly represents the device characteristics.

So, if I say that this is our main model of the transistor and we do have the collector terminal here we do have the emitter terminal here and base terminal here. So, that represents this I-V characteristic fairly to good extent. So, we may say that this is equivalent circuit. So, this is equivalent circuit of whatever the BJT we do have here. In fact, being circuit designer we are more comfortable of seeing this kind of circuit, ok.

So, using this model probably we can use we can analyze the circuit. So, we can in the next slide we will see how this equivalent circuit can be you know utilized to analyze the circuit; so in the, yeah.

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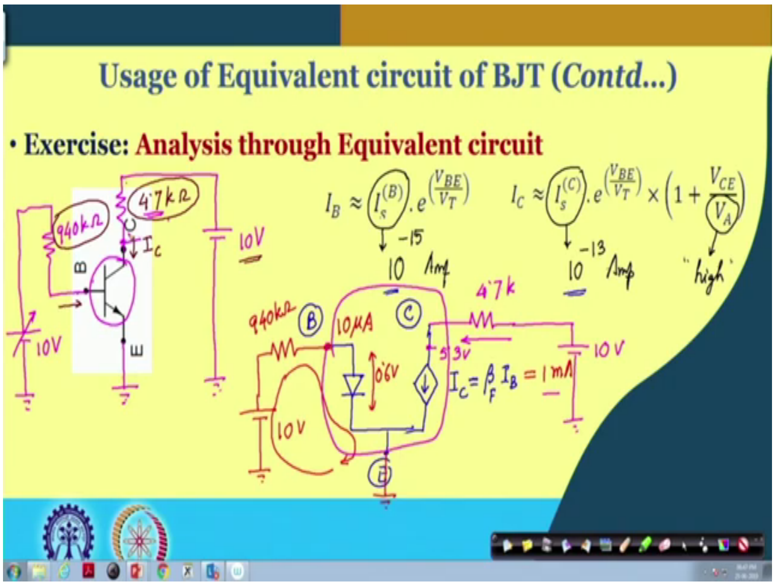

Usage of Equivalent circuit of BJT (*Contd...*)

- **Exercise:** **Analysis through Equivalent circuit**

$$I_B \approx I_s^{(B)} . e^{\left(\frac{V_{BE}}{V_T}\right)} \qquad I_C \approx I_s^{(C)} . e^{\left(\frac{V_{BE}}{V_T}\right)} \times \left(1 + \frac{V_{CE}}{V_A}\right)$$

So, what you can try to do in this exercise probably, let me connect this to ground and let me put a register here and let it consider we do have a voltage source with respect to ground and let me consider this is 10 volt. And, here also we are putting a register we frequently we will be seeing this kind of circuit in later discussion and let me consider this is also 10 volt. And let me assume that this is say 940 kilo ohms and let you consider the other one maybe 4.7 kilo ohm.

Now, to move forward let me assume that whatever the condition we do have most likely the device it is in active region of operation. Namely, this assumption is getting forward biased; obviously, we obtain volts. So, even though we do have high resistance here that is still it is making base to emitter junction forward biased. And of course, then we do have the base current is getting multiplied by beta. So, then it is having the corresponding collector current. So, then there is a drop across this resistance. But for the time being let me assume that this drop namely 4.7 k multiplied by I C this drop it is less than 10 volt.

So, ensuring that this junction it is still you know in the reverse bias condition. So, the device it is in active region. So, that is the assumption, but end of it we also have to verify. So, let you consider the to calculate this one we need some more information, namely we need this part. So, let you consider this is 10 to the power minus 15, minus 15 ampere and let you consider this is 10 to the power minus 13 ampere and for the time being let me assume that this early voltage it is very high quote and unquote high.

Now, with this condition, so how do you proceed? So, we already have discussed about the equivalent circuit. So, let me draw the equivalent circuit of the transistor, we do have the diode connected between base and emitter and then we do have the current controlled current source assuming that the device it is in proper region of operation. So, I C equals to. Now, if I compare say this I S and this I S if you take the ratio that gives us beta is equal to 100.

So, we can say that beta F is 100 multiplied by I B. For the time being let we are ignoring assuming this is very high. So, this is sufficient to; so, we do not require the additional conducting part and we do have the collector here. So, that is the model of our the BJT Now, around that of course, we do have a ground connection here and then we do have the base resistance base terminal resistance and then we do have the 10 volt and this is 940 kilo ohm.

So, if you see that this diode is getting forward biased and it can be shown easily that if I the method we have followed for the simple diode circuit particularly to analyze this loop then we can see that the current flow through this one it is coming to be 10 micro ampere. So, how we proceed? Either you can go through iteration and you will be finding that this voltage it is converging to close to 0.6 close to 0.6 volt you can assume that the cutting voltage is 0.6 volt with that you can calculate that this current is becoming consistent.

So, that is how I have picked up these numbers. So, that gives a corresponding collector current it is approximately 1 milli ampere, assuming that this is properly getting biased. So, we do have the collector side we do have the 4.7 k and then we do have the 10 volt connected here and so if you see that if one milli ampere is flowing through this resistance we do have 4.7 volt drop. So, the voltage coming here it is 10 minus 4.7, so that is equal to 5.3, so this is equal to 5.3. That is that is good we do have 5.3, we do have 0.6. So, naturally this is getting reverse bias.

So, this gives you some idea, that how do we and in fact, that ensures that device it is in active region of operation. So, this is a simple method of finding the different branch current of a circuit involving BJT. So, this BJT we can as I said we can simply replace by its corresponding equivalent circuit. We can do more practice on this one. In fact, if you increase this register this voltage it will drop and beyond some point this junction it will get forward biased. If you further increase this resistance this transistor it will be entering into altogether different region operation called saturation region.

So, we will be going little more detail with this kind of circuit. In fact, we will be varying this voltage and then we will see that what kind of variation or effect it is coming to the collector side that detail when we will be dealing with the amplifier.

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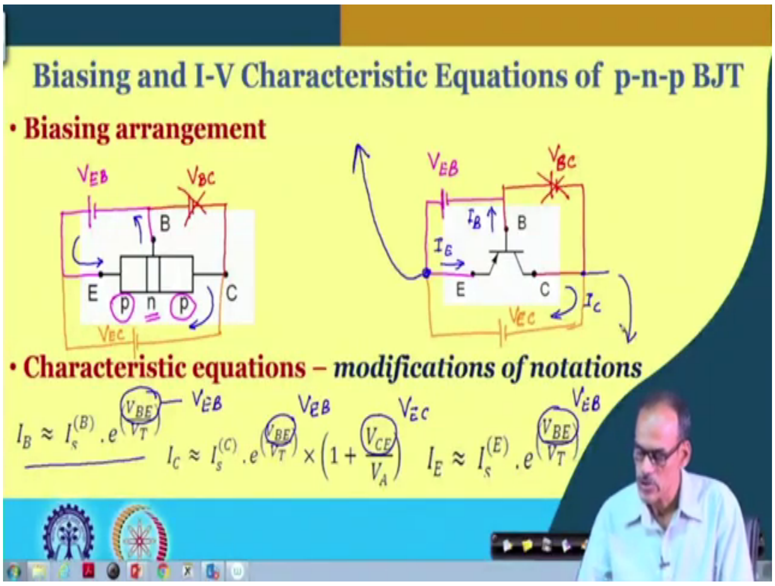

Biasing and I-V Characteristic Equations of p-n-p BJT

- **Biasing arrangement**

- **Characteristic equations – *modifications of notations***

$$I_B \approx I_s^{(B)}.e^{\left(\frac{V_{BE}}{V_T}\right)} \qquad I_C \approx I_s^{(C)}.e^{\left(\frac{V_{BE}}{V_T}\right)} \times \left(1+\frac{V_{CE}}{V_A}\right) \qquad I_E \approx I_s^{(E)}.e^{\left(\frac{V_{BE}}{V_T}\right)}$$

Now, so far we are considering about the n-p-n transistor if you look into the p-n-p transistor on the other hand it is very similar, but of course, it is the 3 islands or 3 regions are different. Namely, we do have p region and then n region and then p region, so we do have p-n-p. And here also to keep the device in an active region of operation base and emitter junction need to be a forward bias which means that at the emitter now we are looking for higher voltage with respect to the base.

On the other hand, the other junction the base to collector junction we like to keep it is in reverse bias, namely the base should be at higher potential with respect to the collector. So, this is the corresponding symbol. So, here, so we may we may consider that the bias here we require such that base at a higher potential and the emitter also at higher potential with respect to on the other hand base. So, we do have higher potential here.

So, either we put the V since the positive side we are connecting to emitter we call it is V EB. So, actually it is V EB, so here also we do have V EB. On the other hand, we do have the other voltage this is V BC. So, V BC it is ensuring the second junction it is in reverse bias and similar to the previous case instead of using this convention or this kind of bias probably we can use the bias elsewhere namely with respect to emitter.

And, if it is sufficiently the collector it is made sufficiently negative with respect to emitter that ensures the second junction base to collector junction in reverse bias condition. So, same thing here also in this view; so, we will be calling this voltage it is V EC. So, we call this is V EC. Note that this for actual operation V EC should be positive V EB should be positive that that is how we are ensuring the device it is in active region of operation. And also if you see based on the polarity of the voltage you can expect the current it will be flowing in this direction.

In other words, the emitter current entering to the device and the base current it is emerging out of the base and the collector current also it is emerging out of the collector. So, that is the axial direction of the currents. So, you may say that this is the actual polarity a positive direction of the current and. So, we do have I E, we do have I B and then we do have I C like this.

So, if you compare the notation or seem the equation we have used for BJT this n-p-n BJT with p-n-p what you can see here it is. So, these are the equations it was used for n-p-n. So, with respect to that we simply have to modify this part namely we can make it V EB. So, likewise here we can replace this is V EB and this is into V EC. So, likewise here also for the emitter this will be V EB.

In fact, if you simply change and if you change the polarity of the current positive polarity of the current in appropriately then the same equations what we have discussed for n-p-n that can be utilized for this circuit also. Now, this is the biasing and the how we change the polarity of the currents and the voltages. For our convenience whenever we will be dealing with this circuit since this node it is having highest potential and this node it is having lowest potential if you see across the device.

So, for better arrangement what we will do we will make this is up and this is down. So, we will simply you know rotate 90 degree this device for our convenience.

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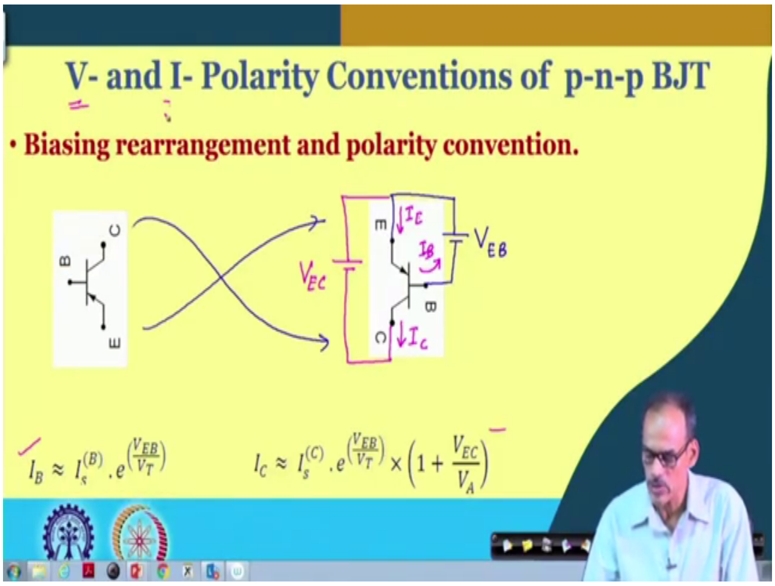

V- and I- Polarity Conventions of p-n-p BJT

- **Biasing rearrangement and polarity convention.**

$I_B \approx I_s^{(B)} . e^{\left(\frac{V_{EB}}{V_T}\right)}$ $\qquad$ $I_C \approx I_s^{(C)} . e^{\left(\frac{V_{EB}}{V_T}\right)} \times \left(1 + \frac{V_{EC}}{V_A}\right)$

So, if you see in the next slide that is how we have done. We have rotated this device and then the corresponding biases are that can be explained like this the, ok. So, this was the previous one and we have rotated. So, we made the collector towards the lower potential, emitter towards the higher potential and here of course, this is p n. So, this junction should be forward biased and this is how the corresponding the battery will be connecting here and we call this is V EB.

So, likewise we can the other junction we can make it reverse bias by connecting V EC and the corresponding equation as I said the collector current it is coming out emerging out of the device the emitter current it is entering to the device. And so, what will be this current? This current of course, it is going out of this device. So, you can say part of this current it is going out here as base current and remaining current it is going to the collector from the emitter.

So, that is about the polarity of the bias voltages and the corresponding currents. And rest of the things it will be similar namely the equivalent circuit and so and so. So, let us look into that the equivalent circuit and the maybe little bit about the graphical interpretation also. I think I do have separate slide for that.

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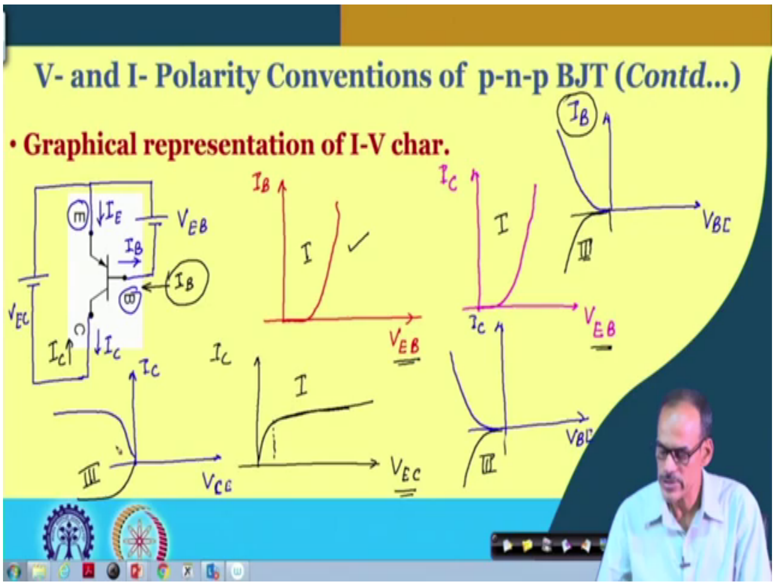

V- and I- Polarity Conventions of p-n-p BJT (*Contd...*)

- **Graphical representation of I-V char.**

So, going back to whatever the biases we do have here. We do have emitter to base bias here and emitter to collector bias here. And the corresponding base current is in this direction, corresponding emitter current is getting into the device through the emitter terminal and this is I B, this is what you say V EB and the collector current is coming out of the device and this is V EC.

Now, you may recall whatever the graphical interpretation we do have or representation of the I-V characteristic of say I B has function up now V EB. So, if you plot this characteristic of course, it will be exponential in this like as you have discussed before. Similarly, when you when you plot the I C versus V EB. So, V EB it will be of course, like this and the I C versus, I C versus V EC not V CE, it is V EC. And here also it is having similar kind of nature because of early voltage it is it is having some slight bend and till it is entering into the saturation region.

Now, since we do have V EB here and here, and V EC instead of V CE that makes a slightly different kind of convention with respect to n-p-n. So, sometimes people try to plot I B versus, so I B versus V BE. So, actually it is supposed to represent this characteristic and since we are flipping this polarity of the voltage here of course, this will be moving to the second quadrant. So, likewise if we plot the I C versus V BE. So, here also if we change the polarity of this bias here also it will be in this quadrant; so, likewise if we consider I C versus V CE that will be in the second quadrant.

And further to that if you say that no you like to keep the similar kind of convention of the current as well. So, then you need to change the polarity of this current similar to the similar to the n-p-n transistor and then if you follow this one. So, what you will get here it is this if you change the polarity of this one and then of course, these two are having opposite sign, so naturally the corresponding characteristic it will be coming to the third quadrant.

So, if you there are two ways of dealing with n-p-n and p-n-p together either you can use the same convention for n-p-n and p-n-p, but then you should be careful that then the corresponding characteristic curve instead of sitting at the first quadrant it enters to third quadrant. So, same thing for in fact, I C you also if you follow the convention positive collector current convention it is entering the entering to the device through collector terminal. So, in that case approach the this current it will be going to the third quadrant and same thing here also it will be entered into the third quadrant.

So, we will be discussing this one later, but just to make it aware that there are two approaches to go from n-p-n to p-n-p, namely change the polarity appropriately for p-n-p keeping the I-V characteristic in the first quadrant itself or you can you know follow the same convention of that of n-p-n, but then the corresponding characteristics are entering to the third quadrant. So, probably whenever the situation comes we will be going in detail of that.

Now, similar to similar to the n-p-n transistor for p-n-p also we to manage the or to analyze as a circuit containing p-n-p transistor we need to replace the transistor by equivalent circuit.

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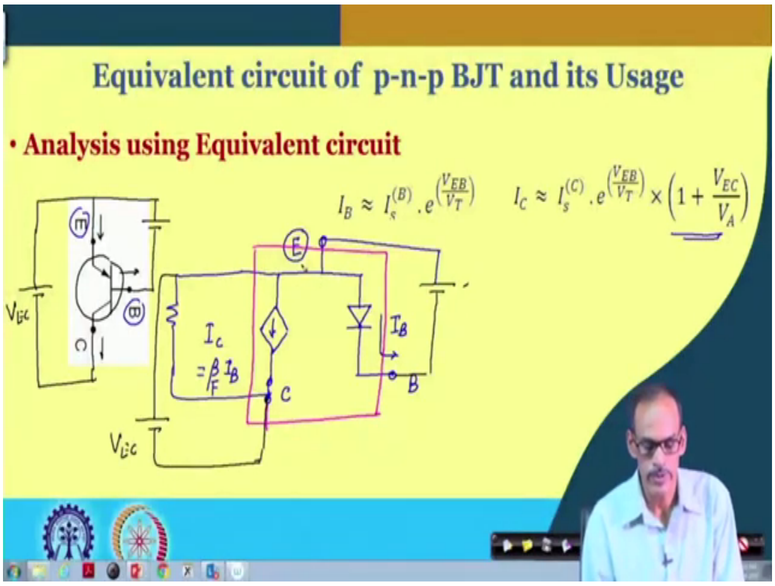

Equivalent circuit of p-n-p BJT and its Usage

- **Analysis using Equivalent circuit**

$I_B \approx I_s^{(B)} . e^{\left(\frac{V_{EB}}{V_T}\right)}$ $\quad$ $I_C \approx I_s^{(C)} . e^{\left(\frac{V_{EB}}{V_T}\right)} \times \underline{\left(1 + \frac{V_{EC}}{V_A}\right)}$

So, probably I do have a separate slide for that. So, we can use this again the same equations and we may have some bias here. Say for example, we may have bias here and we may have some bias here and suppose we are asked to find what may be the corresponding current here, current here and current here. So, instead of really dealing with the equation we may prefer to move to the equivalent circuit. So, base to emitter terminal if you see again we do have a diode

So, we can use this diode. We do have the emitter terminal and we do have the corresponding base terminal. So, we can find, so we can apply the corresponding external bias and then we can find what is the corresponding base current is flowing. And then the emitter to collector you can say that we do have collector current that current it is kind of linear function of the base current. So, we can see that this collector current is beta of the transistor times whatever the I B we do have. So, that is the collector terminal current.

In case if you want to capture these two additional factor of course, you have to consider the conducting path here along with this current control current source. Many here, for many situation in fact, we may ignore this resistance as you have said before for n-p-n and then this is the basic part of the equivalent circuit of the p-n-p transistor.

And then of course, externally we can use the other corresponding bias here. First, we can analyze this part and we can find the corresponding I B current based on whatever the voltage we are applying. So, likewise here we can apply the V EC voltage V EC. So, this is the V EC and you can find what will be the voltage whether this voltage is appropriate or not to keep the device in active region of operation.

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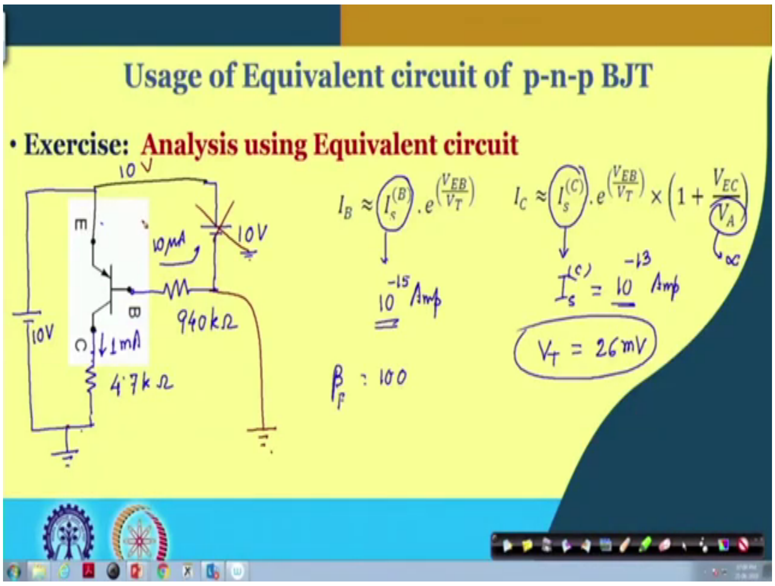

Usage of Equivalent circuit of p-n-p BJT

- **Exercise:** Analysis using Equivalent circuit

$I_B \approx \boxed{I_s^{(B)}} . e^{\left(\frac{V_{EB}}{V_T}\right)}$

$I_s^{(B)} = 10^{-15}$ Amp

$\beta_F : 100$

$I_C \approx \boxed{I_s^{(C)}} . e^{\left(\frac{V_{EB}}{V_T}\right)} \times \left(1 + \frac{V_{EC}}{\boxed{V_A}}\right)$

$V_A \to \infty$

$I_s^{(C)} = \underline{10}^{-13}$ Amp

$\boxed{V_T = 26\text{mV}}$

So, similar to n-p-n let me simply refer to one numerical problem. So, let you consider similar situation let me try to understand that what kind of changes we do have here. Let me have say again 10 volt and again let me put the resistance of 940 kilo ohm. So, we do have 10 volt and here we can put a resistance of 4.7 kilo ohm and we do have 10 volt.

I am using the all the parameters are similar and say let me consider this I S B is equal to 10 to the power minus 15 ampere and I S C reverse saturation current if you call it is reverse saturation current. So, this is I S C for the collector terminal it is 10 to the power minus 13 ampere and similar to the previous case let me assume that this is very high, ok.

And, if you analyze this circuit again of course, we need to get this V T, you may use 26 milli volt typically that is what we do for at room temperature. So, here also you can see that the voltage coming here it is the drop here it is close to 0.6, the voltage coming here it will be whatever the voltage you do have plus this i r drop the base current it is 10 micro ampere and if I take the ratio of these two, on the beta it is equal to 100. So, that gives us the corresponding collector current is approximately 1 milli ampere. So, the drop across this one is 4.7.

So, if I say that this is ground this is 10 volt with respect to 10 volt we do have another 10 volt here of course, this is also going to be ground. So, in that case, so we do have this voltage it is 4.7. In fact, since we do have the same voltage you need not to use this voltage, you may simply remove this one and you can simply connect these two ground, you will be getting the same circuit because we do have this is 10 volt from this one and this is also 10 volt, so this is we call this is common terminal.

So, even if you are not using this one you can connect the circuit like this. And, we will be going a little more detail of the circuit later.

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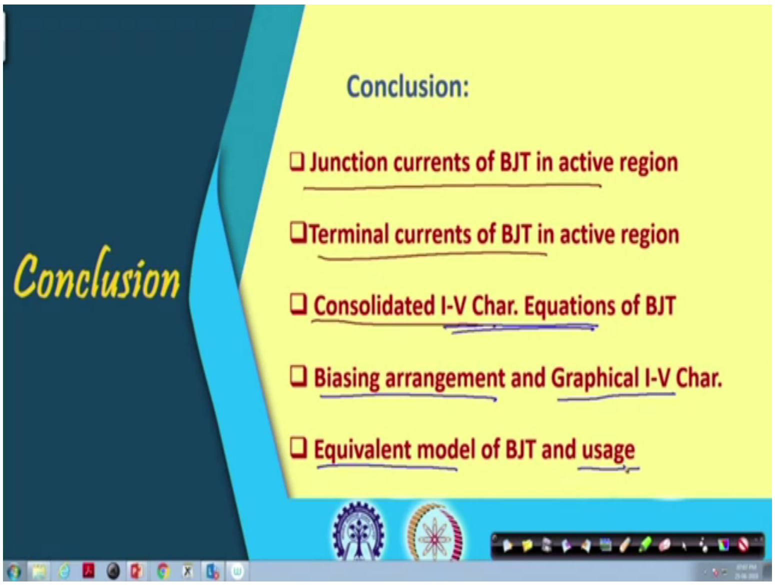

Conclusion

Conclusion:

- ❑ Junction currents of BJT in active region
- ❑ Terminal currents of BJT in active region
- ❑ Consolidated I-V Char. Equations of BJT
- ❑ Biasing arrangement and Graphical I-V Char.
- ❑ Equivalent model of BJT and usage

So, what we have covered so far to summarize in this module. We have of course, in the previous part we have discussed about the; we have discussed about the junction currents and then terminal current of n-p-n transistor and then we have consolidated the I-V characteristic. And, in the second part what we have done is that whatever the I-V characteristic, we obtain from the device we have utilized that to analyze a circuit containing n-p-n transistor. And also we have seen that what kind of biasing arrangement we have to do in actual circuit. We also have seen graphical interpretation of I-V characteristic.

And, then most important thing is that later on we have evolved the equivalent circuit or equivalent model of the BJT both n-p-n and p-n-p. And, we have considered relatively a simple example to illustrate that how that equivalent circuit can be utilized to solve numerical problem of the circuit containing n-p-n or p-n-p. I think, this information it is sufficient to move for the next level namely amplifier design.

Thank you.