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 know 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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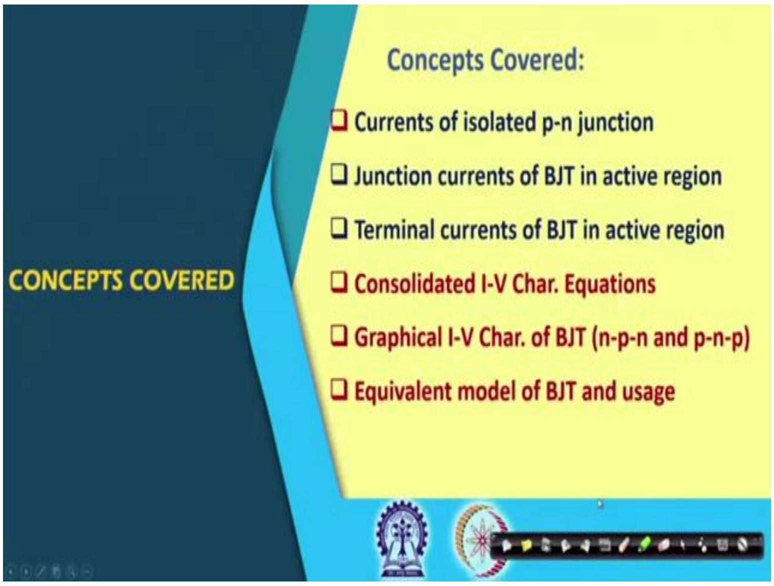

So, these are the concepts we have already have covered the blue colored first 3 items we already have covered and today we are going to the I-V characteristic and how we use the I-V characteristic to analyze say simple BJT circuits. And, also we look into the difference between I-V characteristic of 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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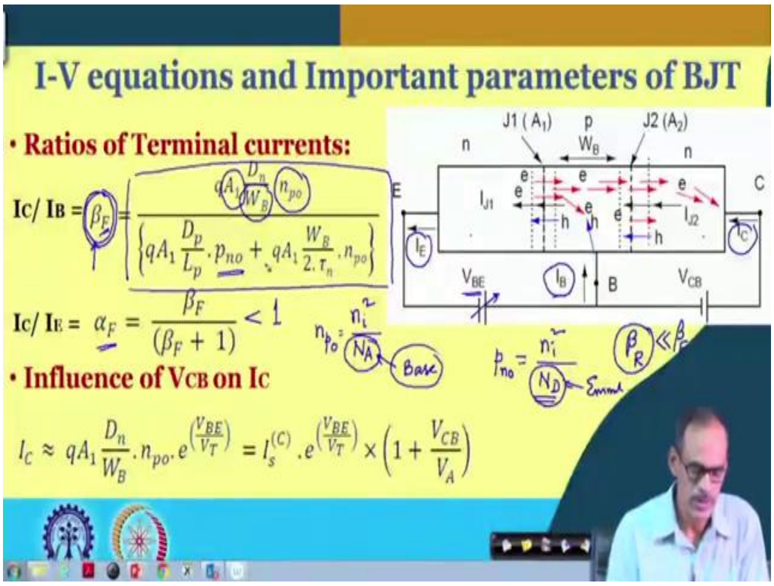

So, let me go to these slides where last we have concluded, yeah. So, this is the slide where we have concluded in the previous part of this module. So, what we have discussed here it is the biasing we already have discussed and then we also have said that how do we vary the junction potential. Particularly, 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 β 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_{po} 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_{po} is nothing but $\frac{n_i^2}{N_A}$ N_A the acceptor carrier concentration in the base. So, this is corresponding to the base region. So, likewise the p_{no} the minority carrier concentration deep into the emitter region; so, that is equal to $\frac{n_i^2}{N_D}$, N_D 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 β should be as high as possible. And this equation reflects that how we can make this β 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 β_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 β_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 β, but you may say that it is in the reverse direction that may be much smaller than in the forward direction β.

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 α_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 β_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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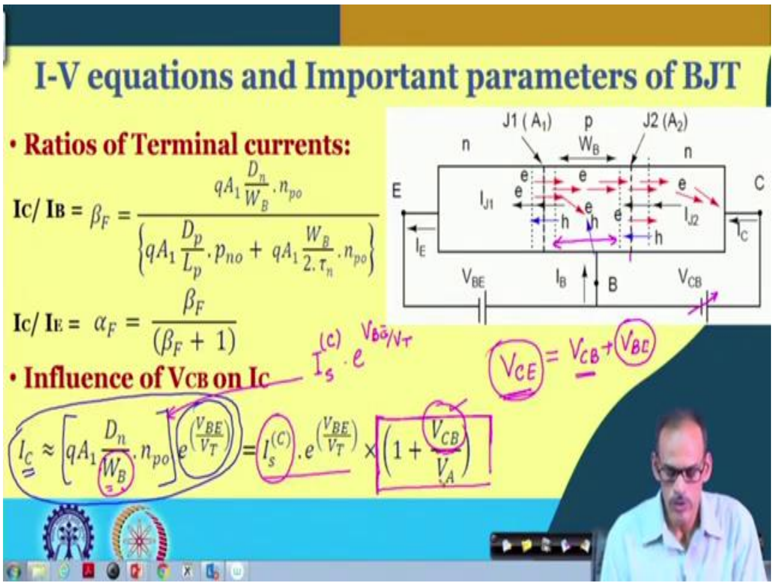

So, as a device user in our circuit we may not be really dealing with tuning these parameters rather we will be assuming that these parameters are given to us. So, as a circuit designer in that case we will be focusing on the current to voltage characteristic relationship, namely I_C as function of the 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 $e^{\frac{V_{BE}}{V_T}}$.

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, and 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} + 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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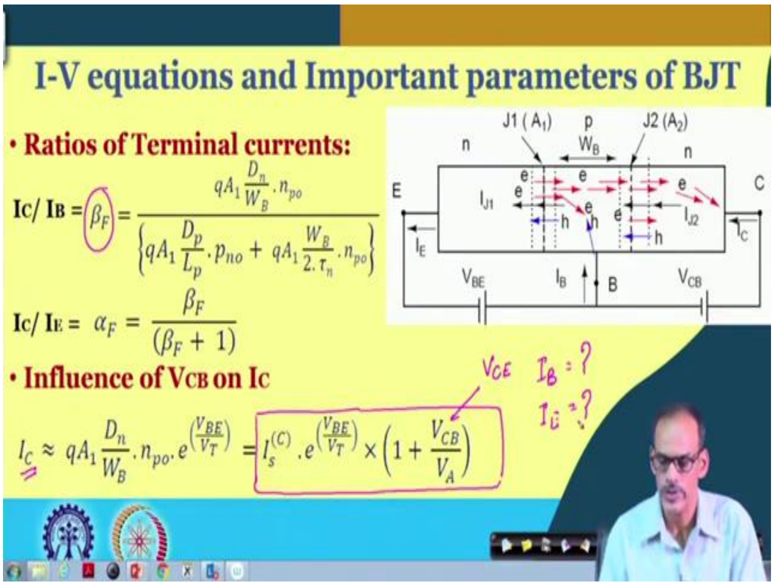

So, end of it what we are getting it is collector current as function of the V_{BE} through this exponential function and it is having a constant and also it is having linear dependency on either you can see V_{CB} or V_{CE}. On the other hand, using this equation this expression of the collector current and using the factor β_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 us go with that into the circuit, particularly a circuit where you do have the BJT.

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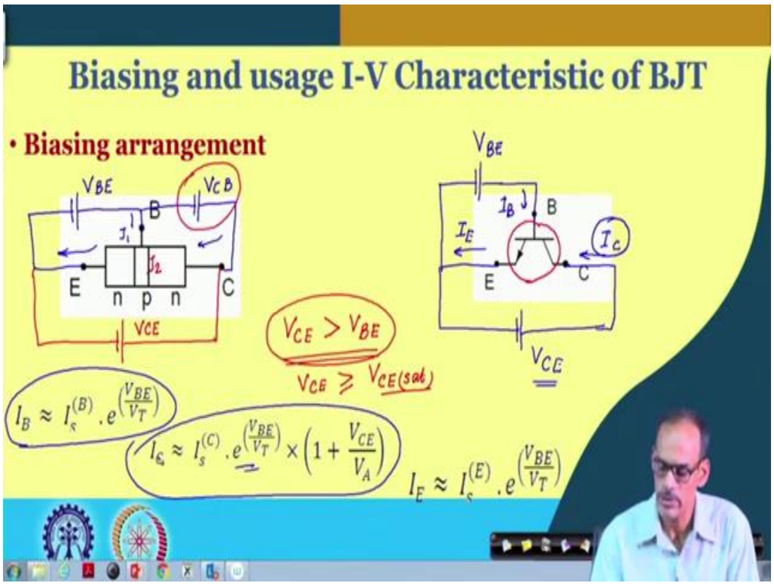

So, here again we are coming back to the little bit towards the biasing side, but if you see that we do have n-p-n transistor. And, then we do have the two junctions of this transistor base emitter junction we like to make it forward biased for active region of operation of the device or to be more precise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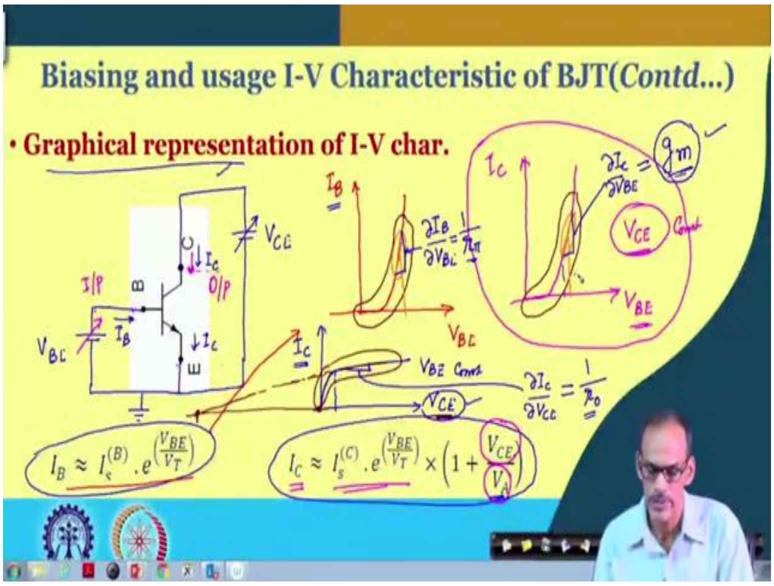

Now, we have oriented the device differently. So, we do have the base we are taking towards the left indicating that probably this will be one of the input terminal. And emitter we are to taking down, so we may be assuming that lowest potential of the circuit may be connected to this emitter terminal 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 applications 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 $-V_A$. So, this is this that represents that at $V_{CE} = -V_A$ 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 may be 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 $\frac{\partial I_B}{\partial V_{BE}}$. So, likewise here the slope it is $\frac{\partial I_C}{\partial V_{BE}}$ 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 terminals current to input port voltage. So, you may say that this is nothing, but 1 by input port resistance, it is $\frac{1}{r_\pi}$. So, likewise if you see the I_C versus V_{CE} characteristic curve, so this slope it is also having interpretation as the output port conductance or $\frac{1}{r_o}$, r_o is the output port resistance.

Of course, this r_o it is small signal resistance r_π 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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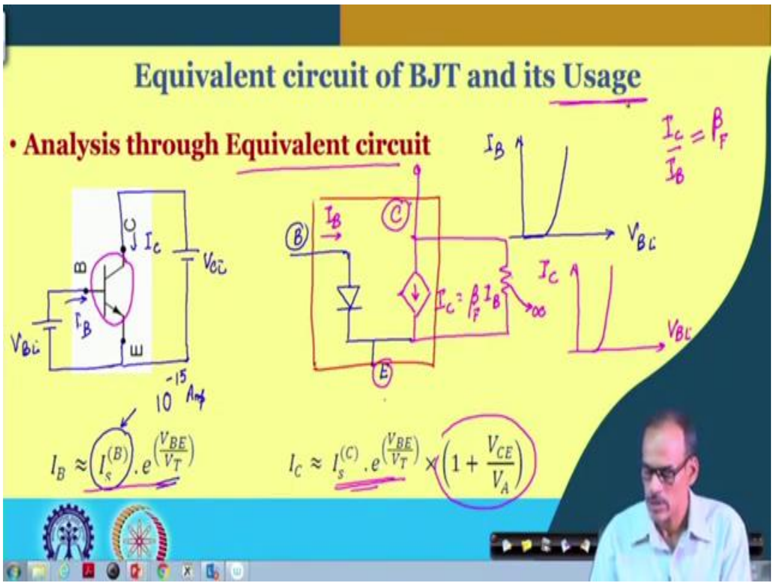

So, if we see how do we then in actual circuit how do we use this equation. So, that is probably very important for the circuit analysis. So, I again I am going to use the same kind of bias here probably we can keep the bias V_{BE} here. And then we can have the V_{CE} and our main interest is to find 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_{BE} characteristic curve it is having similar kind of behavior of a diode. So, I_B versus V_{BE} 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 –15 Amp in comparison with diode, if I say that for a typical diode normal signal diode this will be 10^{-13} Amp 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 ports 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 $\frac{I_C}{I_B}$ it is quote and unquote remains constant. So, whatever β_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 $I_C = \beta_F \times I_B$. 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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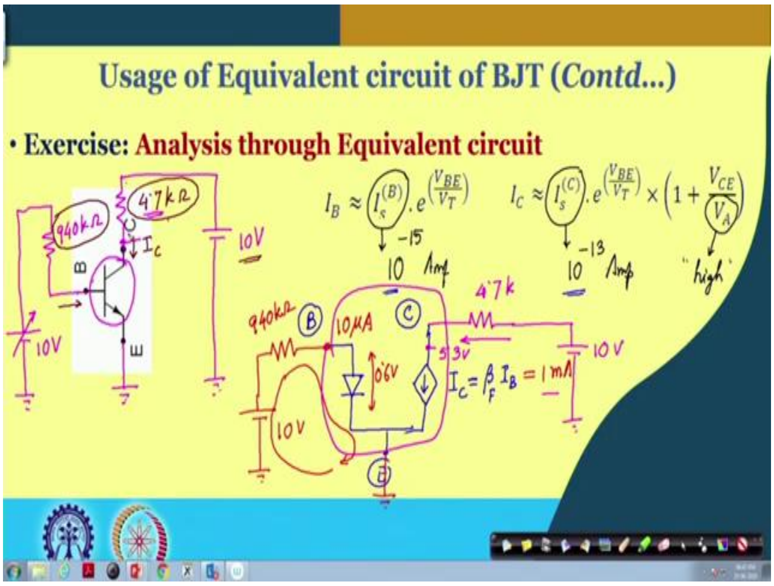

So, what you can try to do in this exercise probably, let me connect this to ground and let me put a resistor here and let it consider we do have a voltage source with respect to ground and let me consider this is 10 V. And, here also we are putting a resistor we frequently we will be seeing this kind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

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 β. 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 × I_C this drop it is less than 10 V.

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^{-15} Amp and let you consider this is 10^{-13} Amp 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 $\beta = 100$.

So, we can say that β_F is $100 \times I_B$. 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 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 V and this is 940 k**Ω**.

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 µA. 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 V you can assume that the cut-in voltage is 0.6 V 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 mA, 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 V connected here and so if you see that if 1 mA is flowing through this resistance we do have 4.7 V drop. So, the voltage coming here it is 10 – 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 resistor 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.