Solid State Devices
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Lecture - 30
Bipolar Junction Transistor (Contd…)

So we have been discussing the bipolar junction transistor. So far we have considered the basics of transistor action and then we have seen how the transistor can be used as a small signal amplifier. In the previous lecture we estimated the alpha and beta of the transistor and we drew the energy band diagram. Then we have been discussing the various configurations of the circuit configurations in which the transistor operates that is the common emitter in addition to the common base configuration. In the common emitter configuration we showed that you can gat power gain. That is, in addition to voltage gain you also get a current gain.

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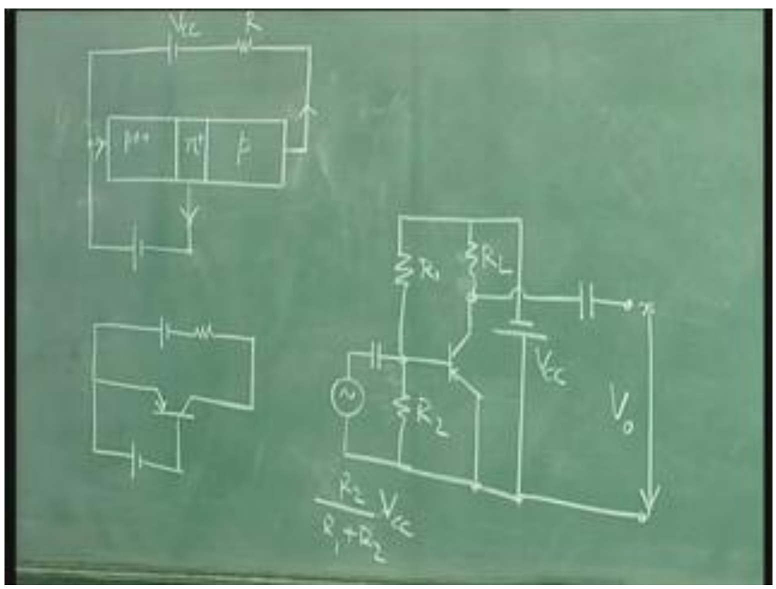

Towards the end of the lecture we were trying to develop from a single transistor and a power supply and a load resistor the complete circuit we normally employ for a common emitter transistor. Let us look at this circuit we have drawn in the previous lecture. We came to the circuit, starting from here this is the basic circuit, we replaced the transistor by symbol and then this circuit has been first turned 90 degree so anticlockwise you turn it 90 degree and that is how you come here, replace this particular power supply by a pair of resistors so you are deriving the emitter base power supply from the collector power supply using a voltage divider. So the voltage across the emitter base junction in this particular circuit is given by R_2 into V_{cc} by R_1 plus R_2 so that is the voltage here. The small signal is super imposed through a capacitor connected here which isolates this point from this point for DC conditions.

Similarly, the output is taken from this point through a capacitor so that whatever you connect here, for example, if you connect a load resistor here then this resistor will not affect the DC condition of this particular circuit. Now what we said is that this method of biasing the transistor and getting DC quiescent conditions is not very good because you are trying to maintain the emitter base voltage constant if the temperature of the transistor changes which is going to happen very much during operation because the transistor is going to dissipate power or because the ambient conditions are going to change throughout the day. Because of these reasons for a constant emitter base voltage the current will change drastically as a function of temperature.

So emitter current and collector current these currents will change and your quiescent point output point will change and that will affect your swing capability of the amplifier. Now how do we rectify this problem? So, to rectify this problem what we must do is that we must maintain the emitter current or the collector current constant instead of maintaining the emitter base voltage constant. Then the emitter base voltage can be allowed to change and the change in emitter base voltage width temperature for constant emitter current will not be much. This can be easily seen from the characteristics.

So if you take a diode these are the current voltage characteristics of any diode. Now for a higher temperature your current will be higher so this is your curve for higher temperature. Now what you find is that if you keep the current constant there is a small change in voltage. On the other hand, if you try to maintain the voltage constant then you find that there is a large change in current with temperature so this is for T_1 and this is for T_2 where T_2 is greater than T_1.

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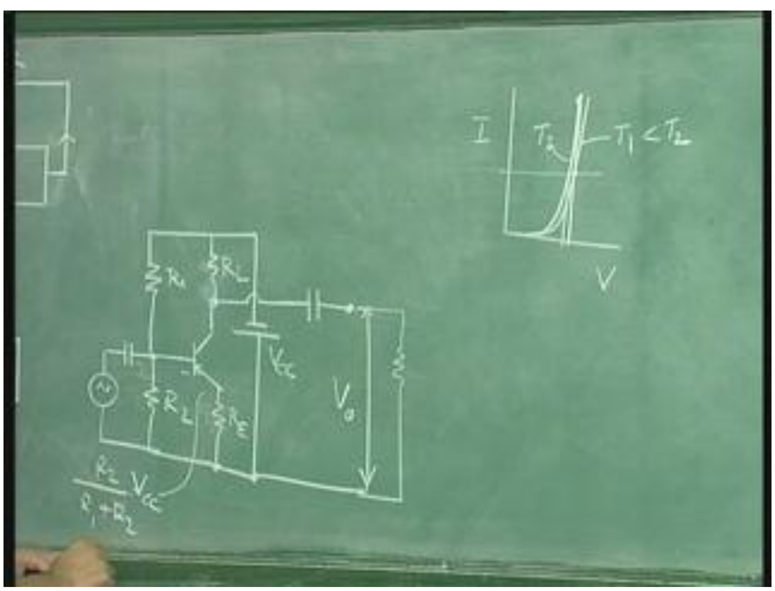

Therefore the idea is to maintain the current constant instead of the voltage being maintained constant. That can be done easily as follows: You include q resistance here in series which is the so called emitter r and you adjust your R_2 so that you have a higher voltage here so that the current in the emitter now is given by this voltage minus the emitter base voltage which is close to 0.65 by R_E. Now your emitter base voltage will be close to 0.56 and it may change little bit because of temperature but the change will be very small compared to the voltage that is coming here.

For example, if you maintain 5 V here, this voltage is chosen to be 5 V then this is 0.65 it may change around 0.6 or 0.7 even if it changes that much it is not much of a change compared to 5 V. A change of about 0.1 volt in 5 V is not much and therefore the current through this resistance will remain almost constant with temperature. That is why it is biasing arrangement is used. It is not in the scope of this particular course to discuss the biasing and circuit aspects of the transistor operation so much, this is done in the circuits course. But still we want to maintain a link between the device physics and the circuit, a discussion of these two.

Now to complete this discussion in order to get a good gain this series resistance must be bypassed so that for AC purposes you do not have this resistance and your gain is still given by a transconductance g_m of the transistor multiplied by load resistance R_L in the absence of this resistance. If this resistance is also present then parallel combination of these two resistances multiplied by gm would be the gain. With this we complete the discussion of the circuit configuration in which a transistor can be used as a common emitter amplifier. Since we have now introduced the common emitter configuration as the most often used configuration let us see the DC current voltage characteristics in detail in this particular mode of operation of the transistor. Common emitter output characteristics: This is the circuit and these are the characteristics. Now we want to qualitatively explain how these characteristics are obtained.

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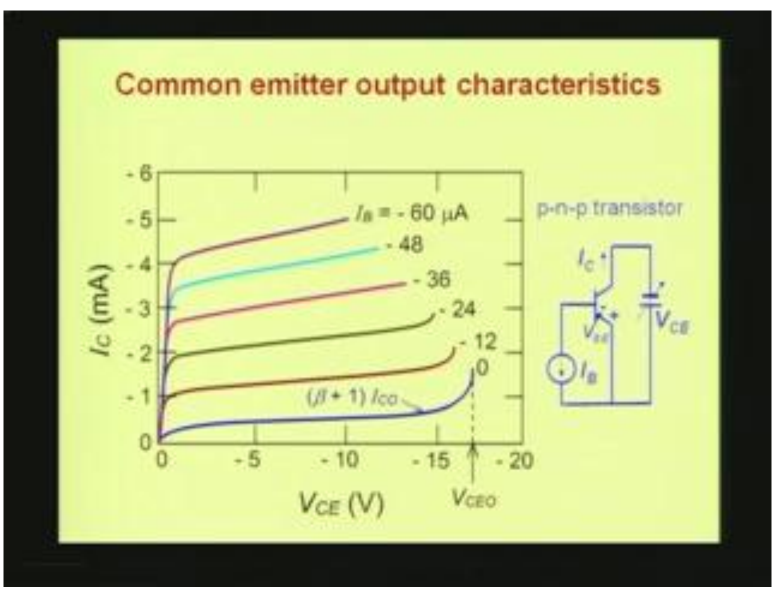

What is happening here is that is you carefully note we keep the base current constant and then we change the collector to emitter voltage and as a result the collector current changes. Supposing you concentrate on any one of these curves let us say the curve corresponding to 36 microamperes base current, you follow this particular curve and what is happening is you are keeping the 36 microampere base current and then you are changing your V_{CE} magnitude and as a result the collector current is changing. If you change your base current you get a different I_C V_C curve and that is how you get this entire family of curves. This is a circuit, you are maintaining the base current constant and you are sweeping the collector to emitter voltage and measuring the collector current. This is what is important to note.

Now what we will do is that we will take up any one curve for constant base current and explain how this kind of a shape of the characteristics raises. Then we will do it for a different base current and that is how the entire family of characteristics can be generated. Now one point to note here is that the collector to emitter voltage is negative because we are considering a p-n-p transistor. This means that collector is negative with respect to emitter. Similarly, the base current also is negative because it is coming out of the base lead and collector current is also negative because it is going out of the collector view. But in our qualitative discussion we will assume only the magnitudes of these quantities so that we do not have to constantly deal with negative quantities. So let us draw one curve that we want explain.

For one base current instead of V_{CE} I am going to draw V_{EC} here so that I get positive voltages. And similarly here I am going to draw modulus of I_C so that I get a positive quantity on this axis also. Now, for any particular base current the curve looks something like this and after sometime it breaks down. How do we get this kind of a curve? Let us start as follows: We draw the transistor and now we are maintaining the base current constant so this is the base current, this is I_B. The first step would be you start from V_{EC} is equal to 0 and this is V_{EC} is equal to 0. So V_{EC} is equal to 0 is point number one and the emitter to collector is shorted. This is the condition V_{EC} is equal to 0. What happens in this case is what we need to find out.

Now our approach would be that we will carry the minority carrier distributions in the emitter base and collector for different voltage conditions. And from the minority carrier distributions we will get the information about the collector current. So here if you draw the minority carrier distribution for these conditions it would be something like this. Now please note that we must try to draw all diagrams to scale. Now this base width is about a micron and I am not saying it is exactly one micron because you know that your depletion width from either side in this region that is from the emitter and from the collector will slightly reduce the base width.

We are now discussing at a qualitative level so we are not interested in the exact magnitudes. So this is about a micron and the diffusion length in the emitter as we have noted is 33 microns. So strictly speaking the distribution of the excess minority carriers would be over a fairly long distance here as compared to the base width. So let us draw this as something like this. This is excess minority carrier concentration in the emitter.

Now we are going to assume long emitters. As we have said in the beginning we assume an ideal transistor. In ideal transistor the doping levels in the base emitter and collector are uniform and the emitter and collector regions are fairly long.

Now what about the excess carrier concentration in the base? According to this, whatever is the emitter base voltage the collector base voltage is also equal to the emitter base voltage because if you have shorted obviously this voltage should be equal to this voltage in magnitude. They will cancel each other and that is how you get a 0 voltage between emitter and collector. This means that from the diode theory the boundary values of the excess carrier concentration would be same at this end as well as this end. So this is your excess carrier concentration in the base.

Now please note that this value could be ten times this value because doping in the emitter is ten times the doping in the base. So this is again not to scale. If I have to show to scale I must raise it up further. So at least approximately to scale, let us assume that this is not exactly ten times but approximately ten times as something like this. Now what happens in the collector? The collector excess carrier concentration would be ten times this value because collector region doping is ten times less than the base region doping.

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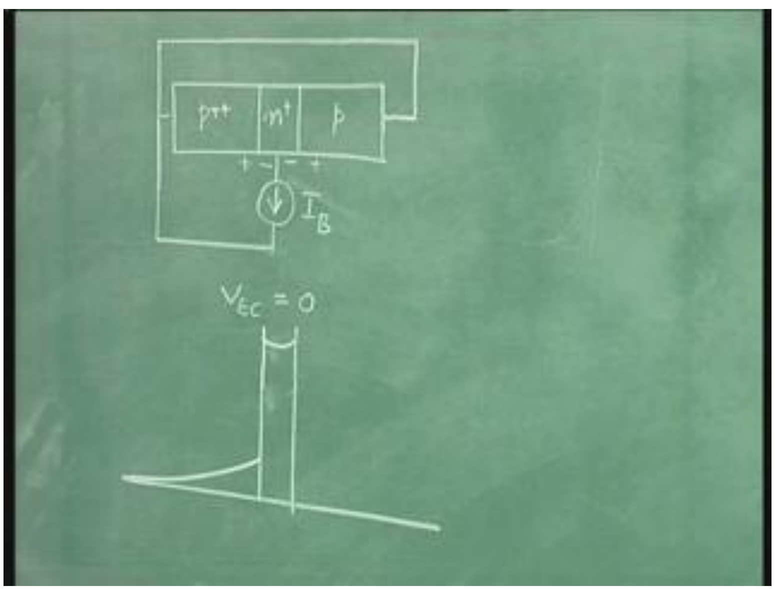

Now this really cannot be shown here. This means that the way we have started the diagram is not exactly correct. The correct approach is always to look at the maximum value and first you draw that value and then draw the other parameters which have smaller value and that is the way you must draw whenever you want to draw the diagram to scale. So, having understood that the maximum concentration will occur in the collector at the depletion edge here of the collector junction what we should do is, let us restart as follows:

So we first draw this excess carrier concentration because this is also forward bias now under this condition. Please note that this is a forward bias across a collector base junction. Now this is one tenth of this inside here so still I cannot show one tenth but at least roughly very small and this here is something like this because this is again one tenth of that. So this is how the excess carrier distribution would be. This is excess electrons in p region, this is excess holes in n region, this is excess electrons again in the p type collector region. From here what do we gather about the collector current? Let us draw the flow diagram to show the various currents here.

What is happening is that this is p, this is n, this is p so electrons are being injected into the collector. We will show dotted line for electrons and all these are recombined. Now similarly this shows that holes are being injected into the base from the collector. Or rather we will reverse this to show the electrons below and the holes above. So the electrons being injected will be shown like this and the holes injected from here are shown this way. So holes are injected into the base from the collector and also from the emitter because both these are forward bias and you can see that the slopes here are like this so these are the holes injected.

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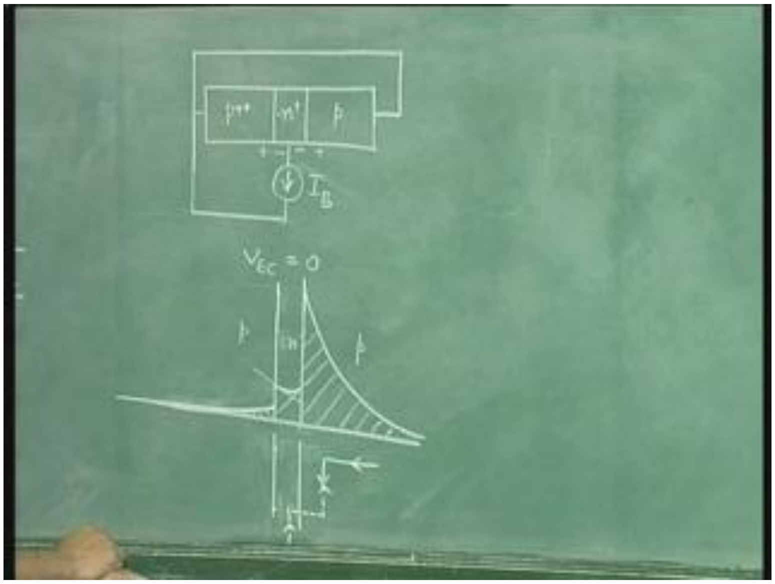

Now what happens to this hole current is obviously it recombines here. Similarly, the base injects electrons into the emitter so you have electrons injected here. Now with what will these holes recombine? They will recombine with electrons. You have to provide electrons there for recombination in the base. So all these electrons are injected into the collector and the electrons which are injected into the emitter and the electron which are recombining with the holes in the base are provided by the base contact. Here these electrons will recombine with holes and this is the so called emitter current and here these electrons will recombine with holes here so this is the so called collector current. Please note that the arrows indicate the direction of flow of the particular carrier and dotted lines are electrons so if electrons are flowing in this direction the conventional current because of electrons could be in opposite direction. So the base current is outward, conventional current is outward but the electron current is inward.

To simplify the picture we will use the fact that in modern transistor the recombination in the base is negligible because base is really very thin. Alpha is therefore decided by the injection efficiency or which is equivalent to same that alpha is decided by the current that is injected from the base into the emitter. So alpha is decided by this current and not recombination here. Therefore what we will do is this part of the picture can be removed to gain a simple understanding of the situation. This is negligible means this also can be neglected so we remove this. This is the approximate picture.

Clearly there is a collector current which is present here and also the base current is equal to the electrons injected here plus electron injected here. Now from this diagram you can very clearly see that the excess carrier concentration in the collector is much more than the excess carrier concentration in the emitter because of the difference in the doping levels and because the forward bias across this junction is the same as forward bias across this junction here the emitter junction. Therefore this current will be much more than this current because the amount recombining here could be much more than the amount recombining here. Therefore we could even remove this picture and we are left with just this picture. This means that there is a collector current which is equal to the base current.

Most of the I_B is flowing into the collector. What is interesting is that the collector current is flowing in so if you look at the characteristics on the slide the collector current is shown to be negative and is flowing out. Obviously what this means is that in this case the current should be shown on the opposite side to the current shown on the slide. This means that when we draw this curve actually it is not correct to say when V_{cc} is 0 the collector current is 0. Actually the collector current is inward into the p-n-p transistor and therefore it is positive or in our nomenclature since we are showing negative currents in this direction the current that we want to show for V is equal to 0 should be shown in the negative axis because negative currents are shown along this particular axis so the positive current should be shown along this axis.

We will now redraw this curve to start with. Now our curve is as follows: For V_{EC} is equal to 0 you have a current which is equal to the base current like this. So this is the I_C corresponding to V_{EC} is equal to 0 equally in magnitude to I_B. That completes the analysis for the condition V_{EC} is equal to 0. For V_{EC} is equal to 0 I_C is approximately equal in magnitude to I_B. Now we can use a similar approach and now proceed to derive the remaining part of the curve. It is very clear from here that the next curve point that you would like to analyze would be you expect the curve to rise up like this. So the next point you would like to analyze would be the point corresponding to I_C is equal to 0. What is the value of V_{EC}? It is this value; V_{EC} for I_C is equal to 0.

Now please note that I have removed the modulus of I_C here and I am just showing I_C. It is understood that we are going to plot the current that is into the transistor on this side and current out of the transistor on this side. So let us now analyze similarly the condition I_C is equal to 0. When will I_C is equal to 0. In terms of this you are moving towards more and more positive V_{EC} as you go in this direction. This means now you are going to include a power supply here in this direction, a small value and then you are going to increase this power supply slowly until you end up getting I_C is equal to 0.

So we start from the base and we remove this distribution that we had earlier in this diagram and then we remove this. Now what happens? This has to remain a forward bias because the current is outward here although the value of the forward bias may change.
So there has to be a current in this direction. So when you apply a voltage in this direction what is going to happen is that this forward bias will start reducing. Now your condition is, V_{CB} is less than V_{EB} as you start increasing your V_{EC}, this is V_{EC}. So when you want to draw the excess carrier concentration for that condition it will be as follows:
So you see that the collector base voltage forward bias is less than emitter base forward bias that is why this concentration here is less than the excess carrier concentration here.

Here again we are using the law of the junction. Now we need to find out for what kind of a voltage condition will the current on the collector become 0 and how can the current become 0? Let us draw the flow diagram again as we have done earlier. Now, when we draw the flow diagram we will continue to ignore the recombination in the base because we are assuming a modern transistor. In a modern transistor the recombination in the base is negligible and that helps us to simplify the picture greatly. Again, you have holes being injected from emitter to base and part of this is recombining here and the remaining is injected into the collector. So this slope here shows that holes are being injected into the collector. Now this slope here shows that electrons are also being injected into the collector from the base. This is shown like this, the electrons being injected from base to collector.

You have electron being injected from base to emitter as we had earlier so you have this also. As we neglect the recombination we will not show this arrow. Now to complete the picture these electrons have to recombine with holes so you have this and these electrons have to recombine with holes so you have this. Therefore this is your emitter current. Now what you find here is, you have electrons being injected from base to collector and you also have holes being injected from base to collector. You are getting these holes because they are injected from emitter to base and recombination in the base is very small so most of them are coming into the collector. So you have holes and electrons moving in the same direction across this collector junction. If you have holes and electrons both moving in the same direction then their current will cancel out if the magnitudes of the holes and electron currents individually are identical. This is an interesting situation here because of which the collector current is 0.

Though you have flow of both holes and electrons since this flow is in the same direction for both carriers you can see here that the holes here are recombining with electrons so there is no current here that we were showing earlier. This is how you get zero collector current.

In fact one can analyze this situation, write down equations and impose this condition that this hole current should be equal to this electron current and one can determine the value of the collector base voltage and the value of the emitter base voltage and therefore the value of V_{EC} for which this condition would occur. So, that completes the discussion about this condition that is I_C is equal to 0. Now the next step is to move ahead like this on this curve.

We can see from this diagram that as you go on increasing your V_{EC} the forward bias here will start decreasing. The forward bias here was maximum when V_{EC} was 0 and when we started increasing V_{EC} the forward bias started reducing so obviously a stage will come when this forward bias will become 0.

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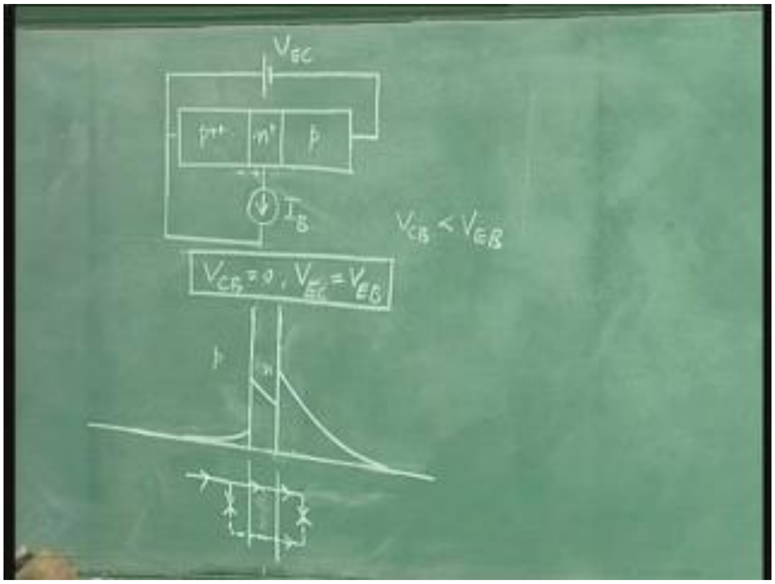

The next step is to analyze the condition when V_{CB} is equal to 0 which is the same as saying V_{EC} is equal to V_{EB}. So this is the next condition we want to analyze. So again now we will erase this excess carrier concentration and will redraw them for the condition that we now have. Now it is very easy to draw the excess carrier concentration for this condition because we have actually analyzed the transistor in the beginning for this condition that is collector base voltage equal to zero. So zero collector base voltage means the excess carrier concentration is zero here. You have this excess carrier distribution in the base then you have this for your emitter and you do not have any excess carrier concentration in the collector because the collector base voltage is 0. In this case you have already drawn the flow diagram, you have holes being injected from emitter to base and a small part of them recombine and then the remaining get injected into the collector.

You have electron current injected from base to emitter and this electron current recombined with holes. These holes which are recombining here need electrons for recombination so this is the electron current and this electron current is supplied by the base. Again we neglect this recombination in the base so we remove this. This is in fact a very simple flow diagram I_C. Now what is the value of I_C in this condition? We know that I_C is equal to beta times I_B. If you want to write I_C in terms of I_B then I_C is beta times I_B. So go up like this and this is the condition corresponding to V_{CB} is equal to 0 and I_C is beta times I_B, so this point is beta times I_B. Again we are not taking into account the fact that the current is outward and it should be negative. We always assume here, for the purpose of analysis, on this board that the currents we are talking of are always the magnitudes of the currents so I_B is the magnitude of the base current. So beta times I_B is the collector current here.

Now, if this is I_B and if this is beta times I_B here then this diagram is not to scale because we have seen that the transistor beta is about hundred for the example we considered. So it can be fifty or it could be even more than hundred it varies but still it is a very large value. So if you want to draw the diagram to scale really speaking this point should be shown very close to origin on the scale. And similarly this voltage is also very small because it is a difference of two forward bias voltages. If you recall the V_{EC} is the difference in forward bias across emitter base junction and collector base junction. So this voltage is also is very small and it turns out as tens of mV.

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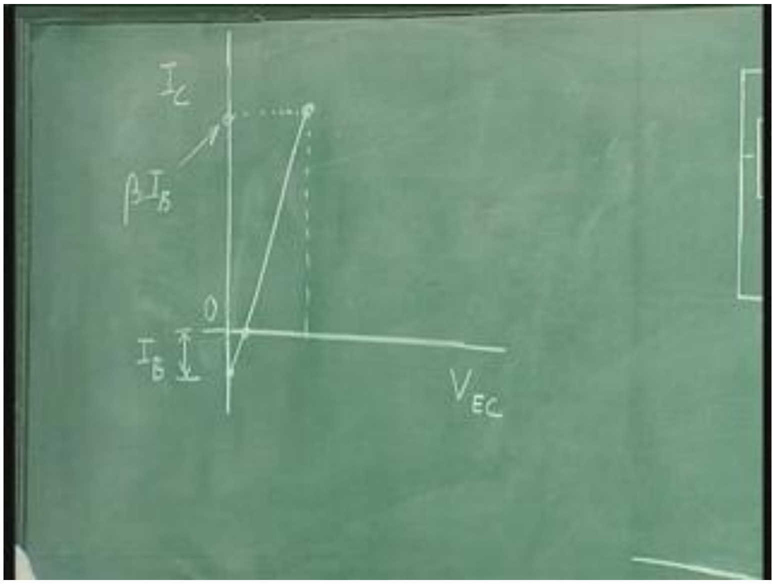

So I_B is microamps or tens of microamps and this voltage is about tens of mV whereas the collector current on this axis is of the order of milliamps and this voltage is of the order of V or tens of V. Therefore on such axis what happens is that this point and this point appear very close to origin. So it is tens of mV on a 10 V axis and microamps or tens of microamps on a mA axis. So this is very close and that is the reason why this point appears to start from origin.

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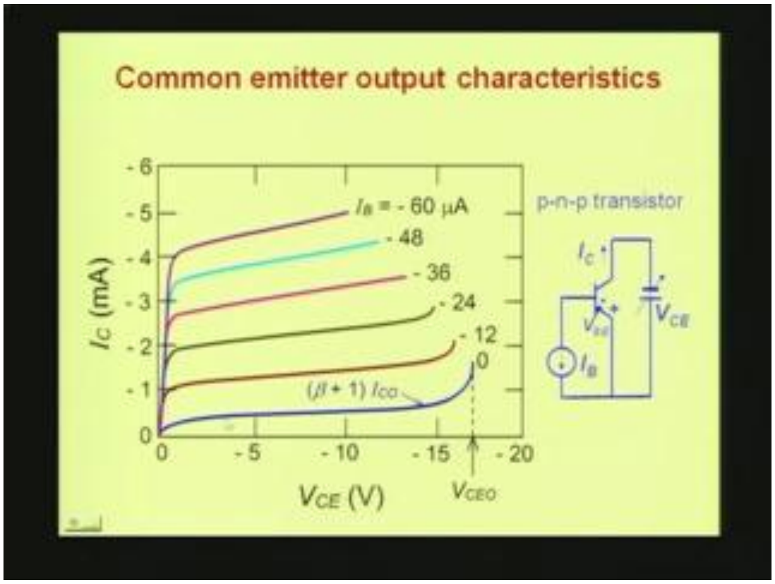

Let us look at the current voltage characteristics on the slide. These currents appear to start from origin. Now we understand from a detailed analysis that the current is not 0, I_C is not 0 when V_{CE} is 0. There is a small current but because the current is very small you really do not see that small amount of current. Therefore these characteristics are shown to start from origin. Now let us proceed further.

What will happen as you increase your V_{EC} further?
So we need to move beyond this, now we are increasing the V_{EC} further. What is going happen is that now your base width modulation is going to come into picture. What is the effect of having a reverse bias across the collector base junction was already discussed in the previous lecture and we said there are two effects. One is, there is a reverse leakage current I_{C0} and another is that there is a base width modulation and this base width modulation has an effect on amplification. Right now we are interested in the base width modulation effect on the I_C V_{EC} characteristics. For that purpose we must now show the base width also clearly. Now let us redraw this diagram.

You have V_{CB} less than 0, collector is negative with respect to base. Now we are showing the depletion region of the collector junction which we have not shown so far. This is the depletion region but again this is not exactly to scale but at least roughly to scale in the sense that depletion region on the collector side of the junction is more than the depletion region on the base side of the junction. Now here once you reverse bias the collector base junction and if the reverse bias is more than three times V_t then we know that excess carrier concentration here would be equal to the negative of the minority carrier concentration so it would be something like this. This is what is responsible for the current I_{C0}.

Now, if you draw this diagram to scale then minority carrier concentration is very small compared to the concentration when there is a forward bias present because when there is a forward bias you know that minority carrier concentration is multiplied by exponential of the forward bias by V_t. So when you draw it to scale in fact you will not be able to show this at all. Therefore the concentration of minority carriers in the collector cannot be shown if you draw the diagram to scale.

Now let us write the equation for collector current in this region, this is the so called active region. This corresponds to V_{CB} is equal to 0 beyond this you have the active region of the transistor and it is in this region that we have analyzed our transistor so far. To explain the transistor action and the amplification and so on it is this region that is very useful because here in this region most of the emitter current is transferred to the collector. What is the equation for I_C? We know that I_C is equal to alpha times I_E when collector base voltage is 0 and when collector base voltage is negative in a p-n-p transistor when it is reverse bias you have this; this is the basic equation for the transistor. Here we want to express in terms of the base current because it is the base current that is being maintained constant. So to do that what we will do is transform this equation so that we write; replace I_E by I_C plus I_B, I_E is equal to I_C plus I_B. So if you do that and rearrange this equation you will get I_C into 1 minus alpha is equal to alpha times I_B plus I_C. Now this is the condition for V_{CB} less than 0 and it is a p-n-p transistor.

Again rearranging this you get I_C is equal to alpha by 1 minus alpha into I_B plus 1 by 1 minus alpha into I_{C0}. This quantity is nothing but beta so your equation is I_C is equal to beta times I_B plus beta plus one time I_{C0}. When I_C is controlled by I_E the current that comes about is not in the collector because of the reverse saturation current of the collector base junction. But when you are controlling I_B and I_C is being controlled by I_B in that configuration you have beta plus one time I_{C0} coming there.

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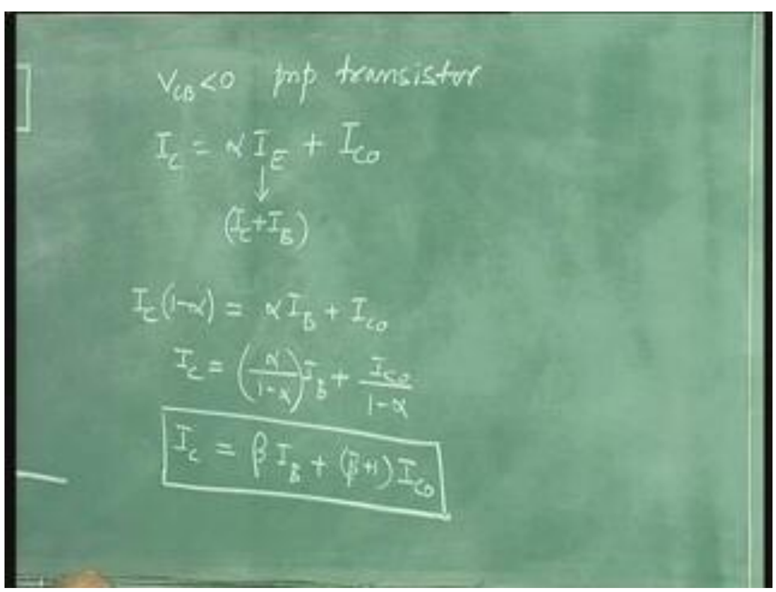

There is a multiplication of this I_{C0} by beta. This is the equation for I_C in this particular active region. Now look at this equation carefully. If we assume that the beta is constant with the emitter collector voltage then I_C should be constant because I_B is being maintained constant and I_{C0} also is constant, we assume temperature to remain constant and I_C should be constant. That means you will have a curve which is just like this which is flat. But when you look in the slide the current is increasing slowly and it is not constant. Now this is because of the base width modulation effect and that is what we have to see here. So because of base width modulation as your collector base voltage reverse bias increases as you increase V_{EC} your base width starts shrinking and this is what you can see here. So, for zero bias you had this particular excess carrier concentration but for reverse bias you have this and if your reverse bias increases you will get this, so this is V_{CB} is equal to 0 and progressively V_{CB} is becoming more negative. Now the collector current will not be constant because you can see the slope is in fact increasing and that is why the collector current will also increase. From excess carrier concentration it is very clear why the I_C increases because of base width modulation.

Now we can actually estimate the extent of increase using this equation which is also another way of looking at it. When your base width is less your beta is more so what is happening in this equation beta is not constant with V_{CE}. So the situation is that beta increases as V_{EC} increases. And this is because base width W_B falls. Therefore because of the increase in beta with V_{EC} instead of a flat current you get a current that is increasing like this, so you have a slope. Let us try to get an idea of this slope because we have tried to get an idea of these magnitudes such as how much is this voltage, how much is this current etc so we should have some idea so that we know how the curve looks like. Now how much will this voltage be? For V_{CB} is equal to 0 this voltage is nothing but V_{EB} this is a forward bias which is about 0.6 0.7 V and this is beta times I_B so this is of the order of milliamps.

Now how much is the increase in current for a certain increase in voltage?
For this purpose we must try to see how beta changes with V_{EC} or in other words how beta changes with W_B. So let us try to write an equation for beta as a function of W_B. We can do this easily because we have written an equation for alpha. Now alpha was 1 minus W_B square by $2L_B$ square minus W_B by L_E into D_E by D_B into N_B by N_E. Now if this is alpha and beta is alpha by 1 minus alpha. Therefore we can approximate numerator as 1 to avoid a complicated formula and 1 minus alpha would be simply this plus this. In modern transistor this term is very small when compared to this term. So 1 minus alpha can be simply written as W_B D_E N_B and L_E D_B N_E. So, for a modern transistor whose beta is governed by injection efficiency and this is the beta. Clearly from here we can see beta is proportional to 1 by W_B. As your W_B changes your beta will increase and let us assume other things to remain constant.

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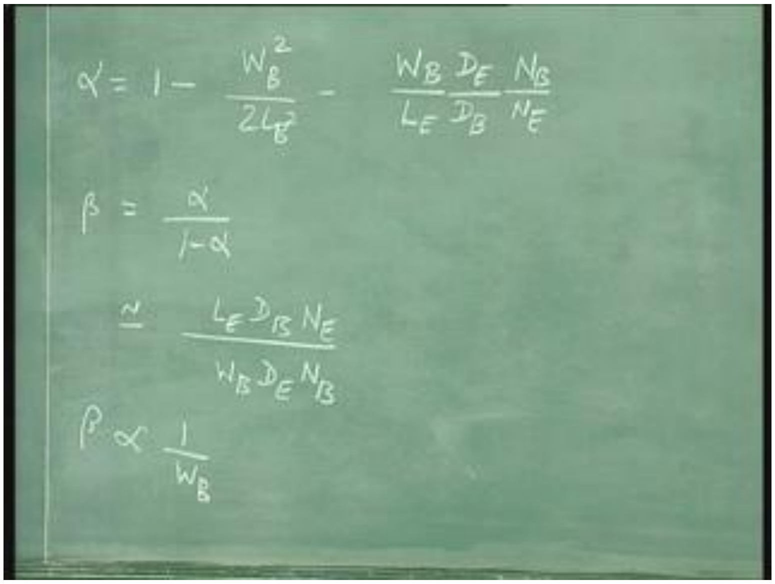

Now, based on this we can try to find out how much increment in current will be there for a given increment in the emitter to collector voltage. We shall denote the value of beta corresponds to V_{CB} is equal to 0 using a symbol $beta_0$. So beta is equal to $beta_0$ when V_{CB} is 0 and similarly the base width is W_{B0} for the same condition. Now we have beta by $beta_0$ where beta corresponds to any other value of V_{EC}. So when V_{CB} is equal to 0 you know that V_{EC} is equal to V_{EB}. Therefore beta is the value for any V_{EC}. So beta by $beta_0$ can be written as W_{B0} by W_B where W_B is the base width for any voltage condition because beta is inversely proportional to W_B.

Now we can write this W_B as W_{B0} minus the change in the depletion width in the base from the collector side, let us call it as delta X_B. What is delta X_B? The delta X_B is the change in the depletion layer on the base side at the collector junction. Therefore this is 1 by 1 minus delta X_B by W_{B0} is your beta by $beta_0$. Now let us see what is delta X_B. This is your collector junction and at zero bias if suppose this is your depletion width this is the base. Now, for any other bias your depletion width will be this. So this is what we are calling as delta X_B. Now this delta X_B can be written as follows. Let us take a specific example, the example we considered, a quantitative example. For that example we found that this depletion width was 0.085 microns and the voltage corresponding to this which was the built-in voltage was psi_0 in the collector junction of 0.637 V.

Let us take a specific case. Supposing I want to find out the depletion width on this side for 9 V reverse bias. So V_{CB} is equal to minus 9 V what will be the depletion width? Now one can find this out very easily. You know that this depletion width will call this X_B so this is X_B. So X_B is proportional to square root of the potential drop across the depletion region.

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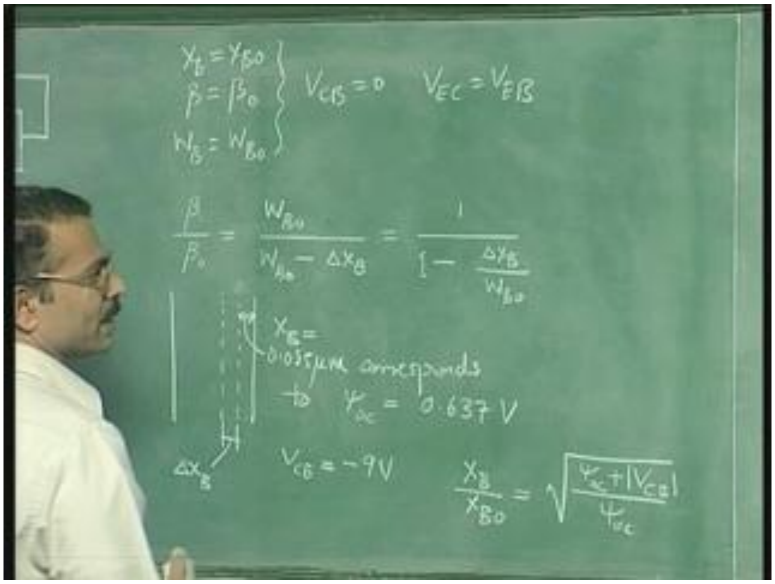

So we will write X_{B0} which is the X_B for V_{CB} is equal to 0 so following this same convention here we write X_B is equal to X_{B0}. X_B is the depletion region on the base side of the collector junction. X_{B0} now depends on psi$_{0C}$ which is the built-in potential across the collector junction. So we can write X_B by X_{B0} is equal to square root of psi$_0$ in the collector junction plus the value of V_{CB} by psi$_0$ of the collector junction. So it is X_B by X_{B0} is equal to square root of psi$_0$ plus V_{CB} by psi$_0$. Therefore delta X_B can be written as X_B minus X_{B0} is equal to X_{B0}(X_B by X_{B0} minus 1 is equal to X_{B0} square root of 1 plus V_{CB} by psi$_0$ C minus 1 in the simplified form. This is the value of delta X_B.

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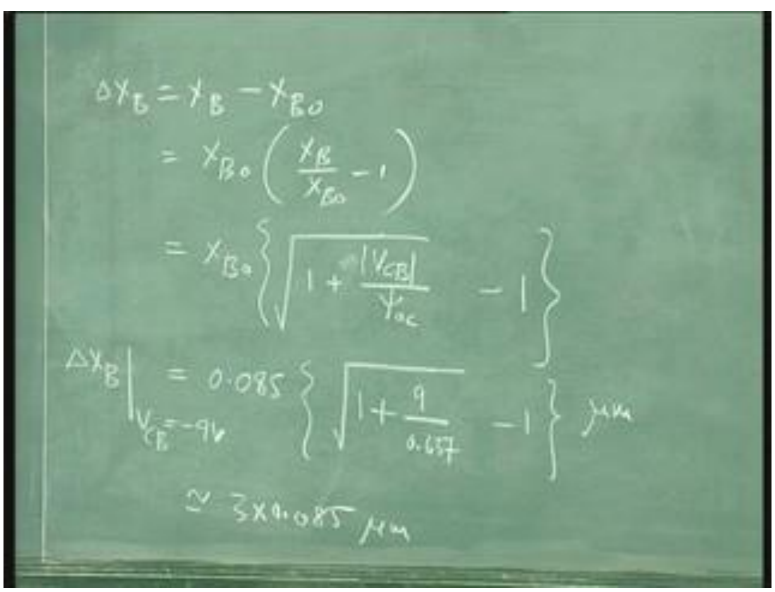

Now substituting the typical numbers from our example delta X_B for, here we are estimating for V_{CB} is equal to minus 9 V. So delta X_B is equal to X_{B0} is 0.085 microns (square root of 1 plus 9 by 0.637 minus 1). This whole thing is micrometer so that is your delta X_B. Now you can use your calculators and try to estimate this value which corresponds to V_{CB} is equal to 9 V negative which we should write here. So it is delta X_B for V_{CB} minus 9 V is the value. So 9 by 0.64 so this will be 9 by 0.6, this is close to 15 and this quantity will be between 15 and 16 because it is 1 plus this. Now square root of 16 is about 4 so 4 minus 1 is about 3 so this is approximately equal to three times 0.085 micrometer that is your delta X_B. Now we can substitute that here and we recall that W_{B0} was about 0.8 microns. When collector base voltage was 0 the base width was about 0.8 microns.

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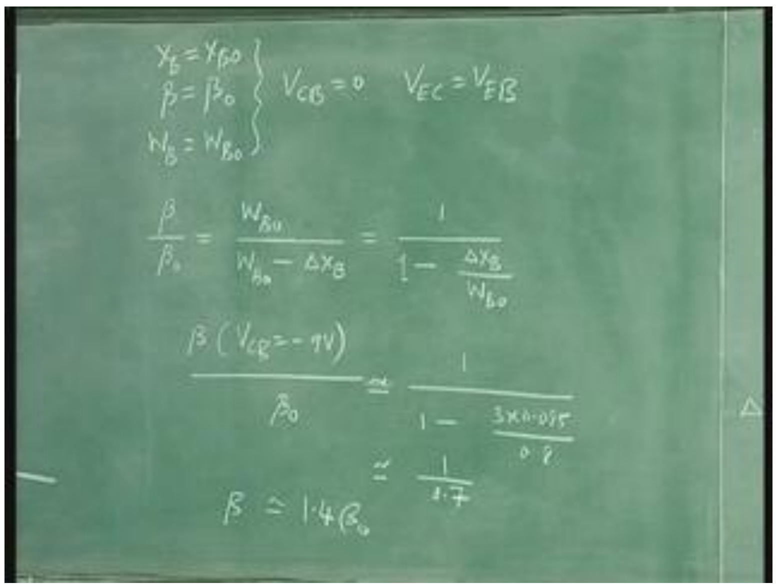

Therefore we can write beta for V_{CB} is equal to minus 9 V by $beta_0$ is equal to 1 by 1 minus 3 into 0.085 by 0.8 which is approximately equal to. This is about one tenth so this about 3 by 10 and this is about 1 by 0.7 which means beta is 1 by 0.7 so it is about 1.4 times $beta_0$ is what you get. This means you find that beta is increasing by forty percent where you will have a lot of change in the character current when you go from this point which is V_{CB} is equal to 0 to the point V_{CB} is equal to 9. So you will have a current increasing from this value to 1.4 times this value. So this gives an idea of how much change in the collector current is there for change in collector to emitter voltage.