**Solid State Devices**
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**Lecture - 27**
**Bipolar Junction Transistor (Contd…)**

This is the 2nd lecture on the topic of bipolar junction transistor and the 27th lecture of this course. In the previous lecture we have seen the characteristics we wanted to explain for this particular device. Then we saw briefly, what is the historical set of events which gave raise to the development of this device. Then we also saw the real structure of a modern bipolar junction transistor and its approximate structure which we are going to use in the analysis of this particular course. So this was the structure we said we are going to use in our analysis.

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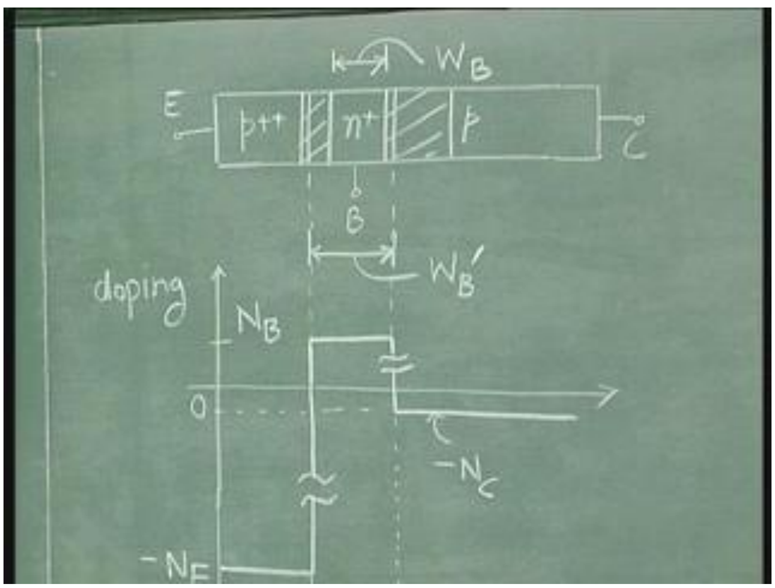

Here all the three regions namely the emitter region, the collector region and the base region are uniformly doped. Further the emitter and collector regions are sufficiently long so that the excess carrier concentrations if any in these two regions decay to 0 by the time you reach the contacts. Now, for this particular structure we will develop the transistor action. Now when develop the transistor action we will start with the simple biasing arrangement as shown in this diagram. Here will assume that the emitter to base junction is forward bias and the base to collector junction is zero bias or shorted. So this is a simple biasing arrangement. Further in this analysis we ignore the space charge region width for simplicity. Later on we will include these widths when we need them. So emitter base junction voltage is indicated as $V_{EB}$, this is the emitter terminal, this is the base terminal and this is the collector terminal.
Now we will be doing a thought experiment, this experiment will involve moving the collector junction to far away locations from the emitter junction and then slowly bring

the collector junction closer and closer to the emitter junction. And then let us see what happens to the various currents in the device and in the terminals. So when this particular collector junction is very far away for that condition we can show the excess carrier concentrations in the device for this biasing arrangement as follows.

We are using the basic PN junction theory here. Since the emitter base junction is forward biased we can show the excess carrier concentrations like this. This is for the collector junction moved far away that is somewhere here so that by the time the excess carrier concentrations reach this point they have already dropped to almost 0. Now, when we say the collector junction is far away from the emitter junction we have to give some feel for the distance.

Now, from the PN junction theory we know that excess carrier concentrations decay exponentially with a characteristic length called the diffusion length. And this we call as the base width and since there is no space charge region shown here $W_B$ is the same as the distance between the junctions. But actually it is the distance between the two depletion edges. Hence, $W_B$ is much greater than $L_B$ for this case and that is the real meaning that the collector junction being very far away from the emitter junction. This is the curve number 1 so one corresponds to $W_B$ by $L_B$ much greater than 1. Now as you move the collector junction closer, let us assume we come to this point supposing the collector junction is somewhere here then your excess carrier concentration can be shown as something like this.

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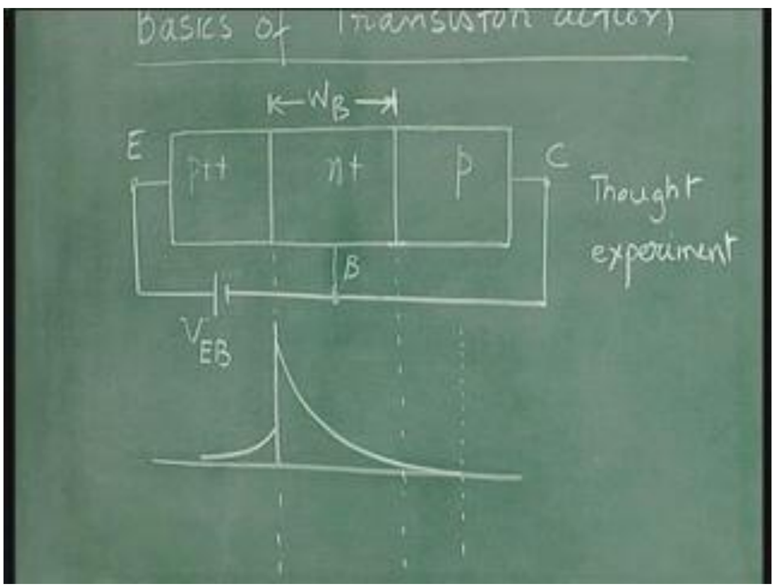


Notice that the boundary value of the excess carrier concentration is governed by the applied voltage across the junction so this is the p-region for example, minority carrier concentration is electrons here so we will indicate the excess carrier concentration as taperal delta $n_E$ at the emitter junction on the p-side boundary. So, delta $n_E$ is the maximum value of the excess carrier concentration of the boundary value of the excess carrier concentration of electrons on the p-side. Similarly, we will denote this as delta $p_E$ this is boundary value of the excess hole concentration at the emitter junction on the n-side. When you come to the collector junction the boundary value of the excess carrier concentration is 0 on either side because this junction is shorted or zero biased.

We are not showing the electron concentration on the p-side because excess electron concentration is 0 because the junction is zero biased. Similarly, boundary value of the excess hole concentration at this collector junction is also 0 either here or there. So this is the curve two which corresponds to a slightly lower value of $W_B$ or lower value of $W_B$ by $L_B$. Finally if your base width is reduced drastically so that you have a condition $W_B$ by $L_B$ much less than one which is the other extreme $W_B$ by $L_B$ much less than 1 that is somewhere here then your excess carrier concentration will look something like this, this is 3. The base width has been reduced drastically. So the excess carrier concentrations for varying base width are shown here.

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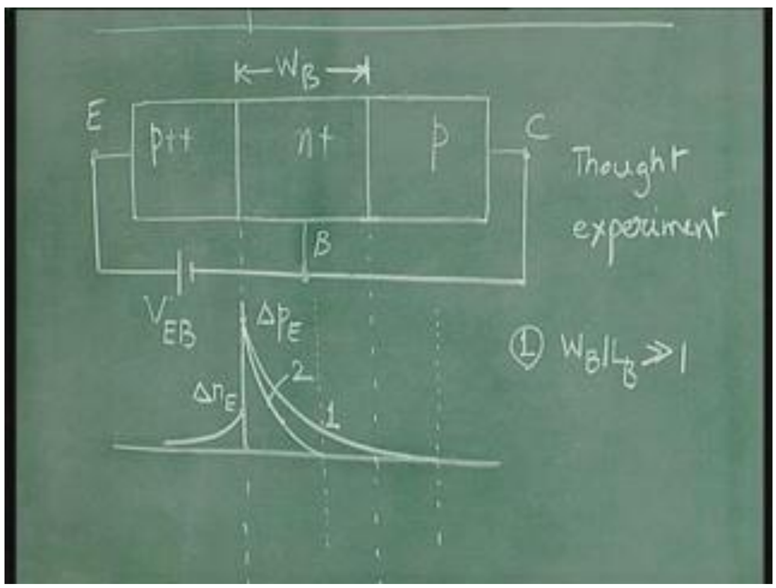


The third experiment we are doing is to find out how the variations of $W_B$ from very high values to very low values affect the various currents in the device. To see the currents we must make use of the flow diagram. You recall when we discussed a PN junction diode we drew a flow diagram showing the flow of holes from p to n-region under forward bias and similarly for forward bias also the flow of electrons from n to p-regions.

This is what we will do here. The flow diagram now can be drawn based on the excess carrier concentrations. So here the flow diagram or the emitter junction would be something like this. The emitter injects holes into the base and the base injects electrons into the emitter. So here we are showing the direction of movement of the carriers. Here these dotted lines show electrons and solid lines show the holes.

Please note that for electrons the direction of current is opposite to the direction of flow. So what we are drawing here is a flow diagram based on the same simple PN junction theory that we have developed earlier. Now what happens to these electrons is because these regions are sufficiently long all the electrons are recombined and that is what is seen here also. The excess electrons concentration is going to 0 by the time you reach this contact. So the electrons are all recombined in this region which will be shown here as follows. So these recombined with holes which are supplied from this contact, this is emitter contact. Therefore, the emitter contact provides for holes which recombine with the electrons which are injected and it also provides for holes which are injected into the base or the n plus region here.

Now what happens to these holes is, if you take the cover one the excess carrier distribution one the hole current at this edge is given by the slope of this distribution is almost 0 because $W_B$ this base width for this particular case one is so large and the excess hole concentration here is going to 0 and slope of this concentration also goes to 0.

Now we know from PN junction theory that the current in a bipolar transistor is because of diffusion in the neutral regions and diffusion of minority carriers which means that the current depends on the gradient of the excess carrier concentration. So the diffusion current of holes here is 0 which means all the holes which are injected into the n plus region or base are all recombined for this particular situation. So, for case one, the picture will be the recombination of all these holes. Obviously they are recombined with electrons which are supplied from the base contact. The base is clearly supplying for electrons to recombine with the holes injected from the emitter and it is also supplying for electrons to be injected into the emitter. This particular component of the emitter current which is due to holes shall be indicated as $I_{Ep}$ and this current which is because of electrons injected from base to emitter will represent as $I_{En}$ and the summation of these two currents is $I_E$. In order to avoid cluttering I will remove these symbols which indicate electron and hole currents.

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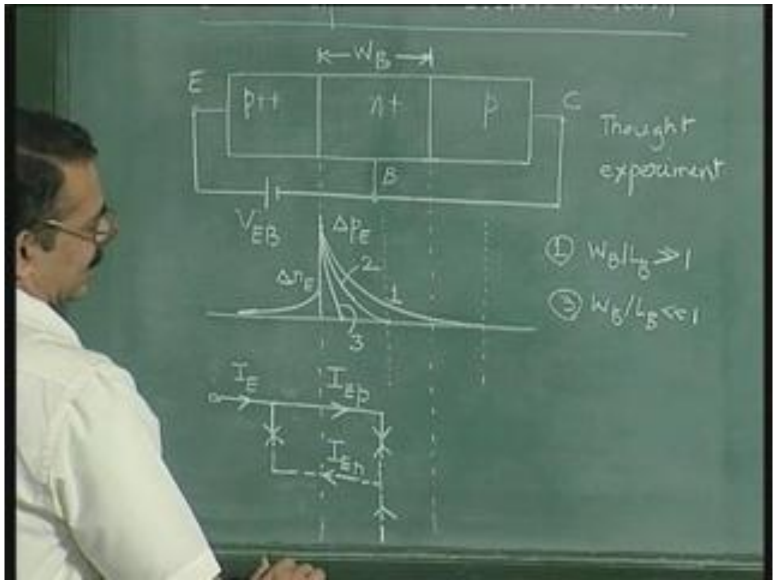


So this will be the picture for case one $W_B$ by $L_B$ much greater than 1. As you reduce your $W_B$, suppose we come to the situation two where $W_B$ by $L_B$ is around 1 then you find that the slope of this distribution of holes here is not 0. So this slope has increased as compared to this case which means that all the holes which have been injected from emitter to base are not recombining within the base and some of these are reaching the collector. This is obvious because the base width is now small and in this region all the holes which are injected are not able to recombine during the diffusion. So what it means is that, for case two we must show a current of holes being injected from base to collector. So this particular slope indicates that there is a movement of holes from base to collector, this is the location of the junction for case two.

Now here, while drawing the flow diagram we will not show the locations of the junction separately for these three cases because that will clutter the diagram. So what we will do is assume that the collector junction is located somewhere here and we are not concerned about the location so we should not try to link this diagram and this diagram. So all that it means is we are going to say that this is the base region and we are going to show what happens within the base region and in the collector region therefore this junction maybe movable as shown here. Now, for case two note all the hole current is recombining but some of it is reaching here.

We can regard the case two as a general situation whose one extreme is this $W_B$ by $L_B$ much greater than 1 and the other extreme is this which is $W_B$ by $L_B$ much less than 1. So here this current which is reaching the collector is called $I_C$ and since this is because holes it is $I_{Cp}$ so this is your collector contact. Notice that even for case to we have not drawn any excess electron concentration in the p-region because this is zero bias and excess electron concentration is 0 at the boundary of this junction and it is 0 everywhere else also so there is no electron current in the collector and that is why you do not have any $I_{Cn}$ for collector base junction bias equal to 0.

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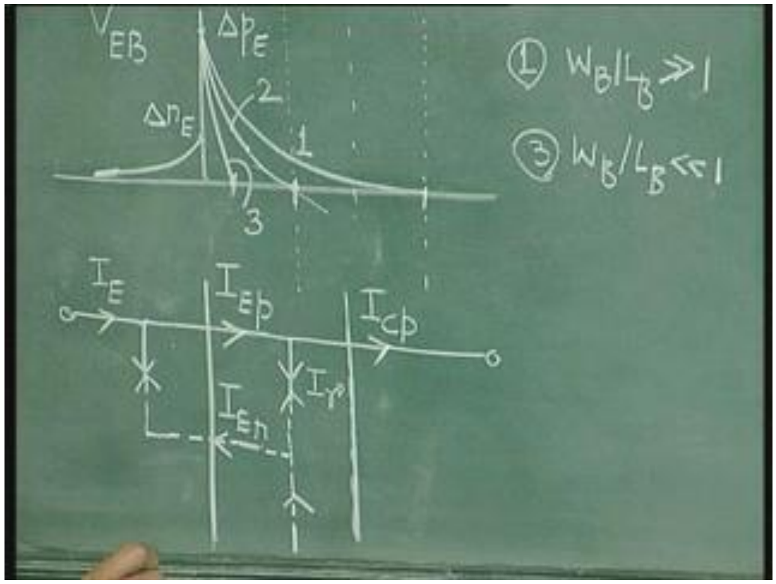


Now let us indicate the hole current recombining in the base by the symbol $I_r$. So this is your base current $I_B$ which is nothing but $I_r$ plus $I_{En}$. The role of the base is to supply electrons for recombination with the holes which are injected from p-region and for injection of electrons into the p-region that is what the shows. So this flow diagram which is shown is generally applicable to all the cases one two and three except that the values of these currents are different for these three cases.

So, for case one, $I_{Cp}$ is negligible are 0 so that $I_{Ep}$ is equal to $I_r$. For case three what we will find is that this slope here at the emitter junction and the slope of the hole distribution at the collector junction are almost the same so this looks like a straight line for very small base width. You can also understand this in a different way as follows. You know that the excess carrier distribution decay is exponentially so E power minus X by $L_B$ or X by $L_B$ in this case because the diffusion length of minority carriers in the base is $L_B$, this $L_B$ is a diffusion length of minority carriers in the base. So, for X by $L_B$ much less than 1 you know that exponential of minus X by $L_B$ where X by $L_B$ is much less than 1 can be approximated as 1 minus X by $L_B$ which means that the exponential decay will be almost linear for very small values of X. This is what is seen here.

So, if your $W_B$ is very small compared to $L_B$ this is the situation then it will almost be a straight line. So this slope and that slope will almost be the same as shown here. We can see this mathematically or we can see this geometrically. In fact geometrical interpretation is much easier to understand and is much more vivid. So, for this limiting case of $W_B$ by $L_B$ which is very small the recombination current will be very small. The recombination current depends on the area under the excess carrier distribution. In fact it is the area under excess carrier distribution divided by the lifetime in that region. We will see this in detail later. But for now qualitatively we need to understand about the various current components $I_{Ep}$ $I_{Ep}$ $I_p$ and $I_{Cp}$ and also the emitter, the base and the collector currents so the $I_{Cp}$ here is same as $I_C$.

The purpose of our analysis is to find out how these components change when you change the base width?
According to the PN junction theory the currents at the junction are because of diffusion of minority carriers and therefore at the junction depletion region boundary the current can be estimated from the slope of the excess carrier distribution. We can get the variations in the various current components as the base width is reduced in our thought experiment.

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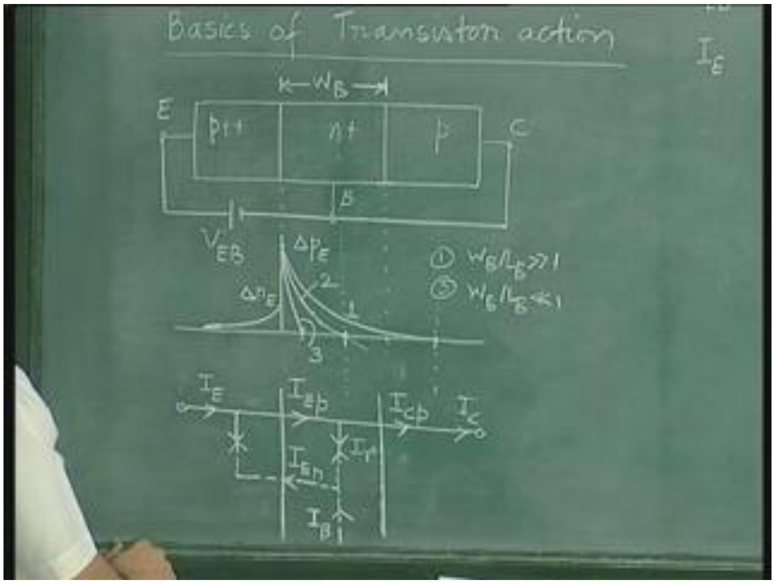


So we will summarize these results on this experiment here. We are maintaining $V_{EB}$ constant. This voltage $V_B$ is maintained constant as you change your $W_B$. As $W_B$ by $L_B$ is reduced this arrow downward indicates reduction which is a progressive reduction up to $W_B$ by $L_B$ tending to 0. Now let us write what happens to the various current components. Let us take the current $I_E$ that is this current. This $I_E$ is $I_{Ep}$ plus $I_{En}$. I want to emphasize that the arrow here indicates the direction of flow of carriers. And since dotted line is for electrons the flow of electrons is in this direction but the current because of electrons is in the other direction which is the same as the current because of holes. Therefore both these currents add up. So $I_E$ is equal to $I_{Ep}$ plus $I_{En}$, as you reduce $W_B$ you find that the slope of the hole concentration in the base is going on increasing, this is very clear.

So, for case one your slope is less and for case two it is more and then for case three it is even more as seen from here. The slope is going on increasing as you reduce $W_B$. Whereas since $V_{EB}$ is maintained constant the boundary value of the excess carrier concentration is constant and it does not change. So, on the emitter side the distribution of electrons is not really changing or the distribution of excess carriers is not changing which means that the slope here is also not changing and therefore $I_E$ remains constant. So $V_{EB}$ equal to constant means $I_{En}$ is constant even as you change $W_B$ but $I_{Ep}$ goes on increasing as you see from the slope. This is what we will write here, $I_E$ is equal to $I_{Ep}$ plus $I_{En}$ where $I_E$ goes on increasing because $I_{Ep}$ increases but $I_{En}$ remains constant.

Let us repeat the same thing for collector current $I_C$ which is equal to $I_{Cp}$ in this case. $I_C$ is nothing but $I_{Cp}$. For very large $W_B$ the $I_{Cp}$ is 0 because the slope is 0. As you go on reducing your base width the slope goes on increasing from 0 you can see this progressively, it is this slope, this slope and this slope. We can write $I_C$ increases because $I_{Cp}$ increases.

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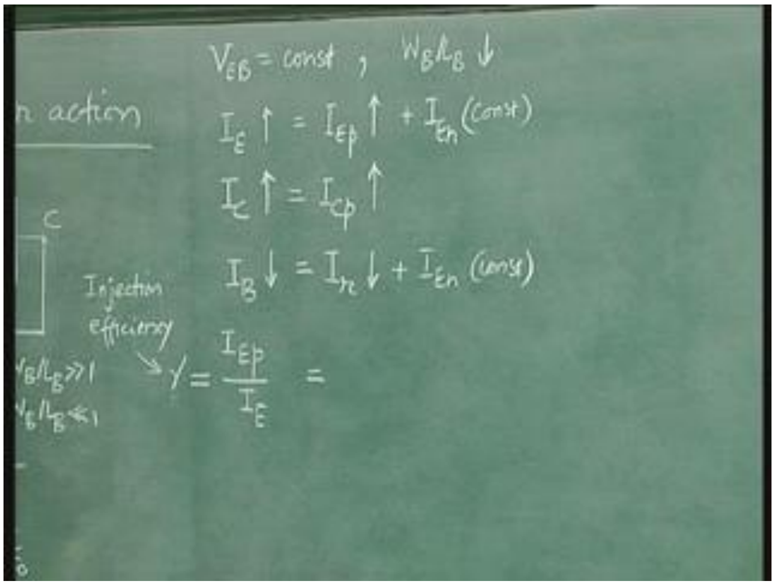


Now, what happens to $I_B$? $I_B$ is $I_{En}$ plus $I_r$ of which $I_n$ is constant and $I_r$ reduces as you reduce your base width because $I_r$ is the difference between $I_{Ep}$ and $I_{Cp}$ and that is the same as the difference between the two slopes so it is this slope and that slope. Now you can see that these two slopes are progressively becoming closer and closer as you reduce your $W_B$. So the difference between this slope and the slope here is less as compared to the difference between this slope and the slope here and it is further less when you come to the curve three. So this slope is almost the same as that slope and it is very evident. Alternately one could also see the area under the curve because as we said $I_r$ is nothing but the area under this curve excess carrier concentration divided by the lifetime.

Since $I_r$ is proportional to the area under the curve it is very clear the area under the excess carrier concentration goes on reducing as you reduce the base width so $I_r$ is reducing while $I_{En}$ is constant. So $I_B$ is going to reduce so $I_B$ falls because $I_B$ is equal to $I_r$ which is falling plus $I_{En}$ which is constant. Now it is of interest to see that the forward bias junction is creating a current in the neighboring junction even though that junction is zero bias as you reduce $W_B$ as seen from here. So a part of the emitter current is coming to the collector as the junction is brought closer and closer and the part which is coming in the collector is increasing as $W_B$ reduces.

Now, at this point I also want to explain why the terminals are called emitter, base and collector. It is very clear from here that this contact is called emitter because it seems to be emitting the current of both holes and electrons. But in the p-n-p transistor it is mostly holes. Clearly $I_{Ep}$ is much greater than $I_{En}$ and this is clear here because doping here is much more than doping here. Doping here is $N_E$ which is much more than doping here which is $N_B$ which is much greater than doping here which is $N_C$. So, because of this the hole current here is much greater than electron current.

Now a part of the hole current that is injected is reaching this contact. It is collecting the current that is remaining after transition through the base and that is why this contact is called the collector. It is collecting the holes which do not recombined in the base. And this is the base contact, if you recall the diagram shown in the previous lecture in the historical development the emitter and collector contacts were on a semiconductor substrate or a base and that is why the third terminal apart from emitter and collector came to be regarded as a base or called as a base. So, because of this particular condition for various currents it is of interest to know the ratio of the collector current to the emitter current.

Now to write this we should recognize that the part of the emitter current is the hole current and part of this hole current is this hole current which is reaching the collector. Therefore we can write two ratios; one is $I_{Ep}$ by $I_E$ what happens to this ratio? This ratio is called the injection efficiency and it is denoted by the symbol gamma. So gamma is injection efficiency.

Why it is called injection efficiency?
It is only the holes which are responsible for the current in the collector. These electrons are not responsible for the hole for the current here. So, if the emitter efficient most of the emitter current should be because of holes so that at least some part of it can be collected because we are not able to collect this electron current at the collector. If you want to efficient device then $I_{Ep}$ by the total current shows the efficiency and that is why it is called injection efficiency. So $I_{Ep}$ by $I_E$ we can write as $I_E$ is equal to $I_{Ep}$ plus $I_{En}$. This is the same as $I_{Ep}$ by $I_{Ep}$ plus $I_{En}$ which is nothing but 1 by 1 plus $I_{En}$ by $I_{Ep}$.

Now we can see what is happening to this injection efficiency. $I_{Ep}$ is increasing but $I_{En}$ is constant so $I_{En}$ is constant and $I_{Ep}$ is increasing which means $I_{En}$ by $I_{Ep}$ is reducing. So 1 by 1 plus $I_{En}$ by $I_{Ep}$ is increasing. So you find that injection efficiency is increasing and for the limiting case of very small $W_B$ you see that the slope is very large. So the $I_{Ep}$ is large as much larger compared to $I_{En}$. Therefore we can say that this quantity tends to unity because this quantity tends to 0 as $W_B$ is reduced, so injection efficiency becomes close to 1.

The second ratio of interest is the ratio $I_{Cp}$ by $I_{Ep}$ so what fraction of $I_{Ep}$ is reaching the collector because a part of it is recombining in the base. If recombination is very small with the entire $I_{Ep}$ will reach the collector and by this way almost entire emitter current will reach the collector if this $I_N$ is small. That is why this is another ratio of interest and we can write this using the symbol B called the base transport factor because it represents what fraction of the current recombines when the holes are transported across the base or what fraction of the current is still retained even after transport across the base. So $I_{Cp}$ by

$I_{Ep}$ we can write as $I_{Ep}$ minus $I_r$ by $I_{Ep}$ so $I_{Cp}$ is $I_{Ep}$ minus $I_r$. And this we can write as 1 minus $I_r$ by $I_{Ep}$.

Now as shown here $I_r$ is already falling as $W_B$ by $L_B$ is reduced and $I_{Ep}$ is increasing. So this is falling and this is increasing so obviously this ratio goes on falling. And in the limit of $W_B$ by $L_B$ it is very small and in fact this ratio will become almost 0. The recombination current here which is dependent on the area under this curve that is this area will almost become negligible so this factor also will tend to 1.

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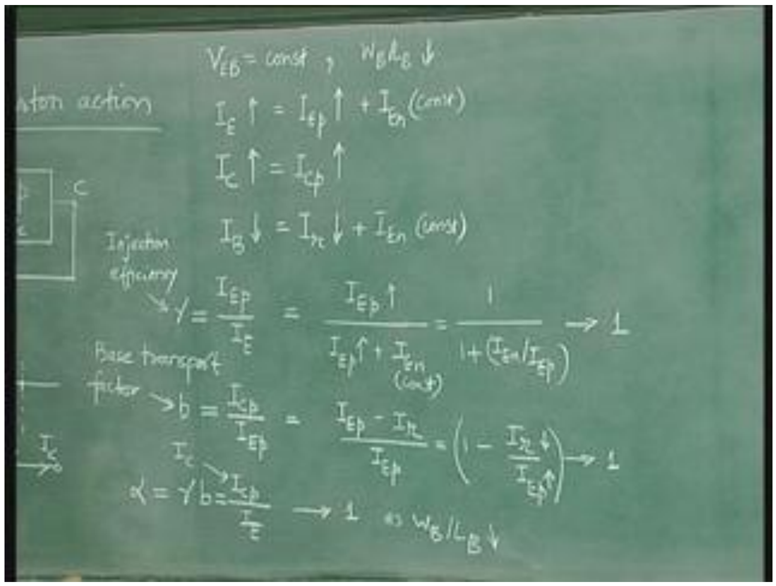


We can now write the ratio $I_{Cp}$ by $I_E$ which is normally called the alpha of the transistor and this alpha is nothing but gamma into b, if I multiply this ratio and this ratio $I_{Ep}$ will cancel and you will get $I_{Cp}$ by $I_E$. Now this ratio $I_{Cp}$ by $I_E$ tends to 1 this is very clear from here as $W_B$ by $L_B$ reduces. As $W_B$ by $L_B$ reduces this alpha of the transistor tends to 1 and this $I_{Cp}$ by $I_E$ is nothing but $I_C$ by $I_E$ so this quantity is $I_C$ for this particular case. So the transfer of current from emitter to collector is almost complete for these conditions.

Now I want to emphasize the conditions for this. The $I_{En}$ should be much less than $I_{Ep}$ that is the first condition so that almost entire $I_E$ is $I_{Ep}$. And the base width should be very small as compared to diffusion length of minority carriers in this region so that the $I_r$ is very small so that the entire $I_{Ep}$ reaches the $I_{Cp}$ under those conditions. Under these two conditions the collector will collect almost the entire emitter current. Now this transfer of current from a forward biased emitter junction to a zero biased collector junction is called the transistor action.

Let us understand the word transistor itself in the light of this explanation has been derived by actually bridging together towards as follows. In these two words transfer and resistor you remove the fer of this word and res of the next word so you have transistor. That is how the word transistor is derived just by collecting this and this. The transfer of current from emitter junction to collector junction this is being referred to as a transfer resistor device, why? It is because, look at the resistance of these two junctions, a forward bias junction obviously has a low resistance than a zero bias junction. So you are transferring the current from across a lower resistor to a higher resistance.

Now obviously if you transfer the current from a low resistance to the high resistance and during the transfer you do not lose the current evidently you are going to have a gain in the voltage and power. For example, if you take the power the power is I square r depends on the current and the resistance. So higher the resistance if the current is same higher the power. Because of this particular action of transferring of the current from a low resistance to a high resistance which looks like some kind of an amplification and to emphasize this fact this device is called a transfer resistor or a transistor.

Now this is the basic transistor action, transfer of current from a forward bias emitter to a zero biased collector or from a low resistance junction to a high resistance junction. And the basic parameter associated with transfer is alpha and this alpha is close to 1 if the doping in the base is less than that of the emitter which is a very important condition because only under that condition this concentration here will be much less than this concentration. The electron concentration will be much less than the hole concentration. That is, $I_{En}$ will be much less than $I_{Ep}$ and the base width should be very small. So necessary conditions for transistor action are $N_E$ is much greater than $N_B$ and $W_B$ is much less than $L_B$. Because of this your injection efficiency is high and the base transport factor is also high. Recombination base in base is small and the electron current into the emitter is small. So under those conditions alpha will be high and close to 1.

Now one can also define another parameter called the beta because just as we can define $I_C$ by $I_E$ we could also define the ratio $I_C$ by $I_B$ and $I_B$ is given here. So $I_C$ by $I_B$ can be written as $I_C$ by $I_E$ which is alpha by $I_B$ by $I_E$ which is further written as $I_C$ by $I_E$ and $I_B$ is nothing but $I_E$ minus $I_C$. So, the directions of currents are like this; $I_E$, $I_C$ and $I_B$. This $I_B$ is the difference of $I_E$ and $I_C$ as written here. This is nothing but $I_C$ by $I_E$ is alpha so alpha by 1 minus alpha and this quantity is called beta.

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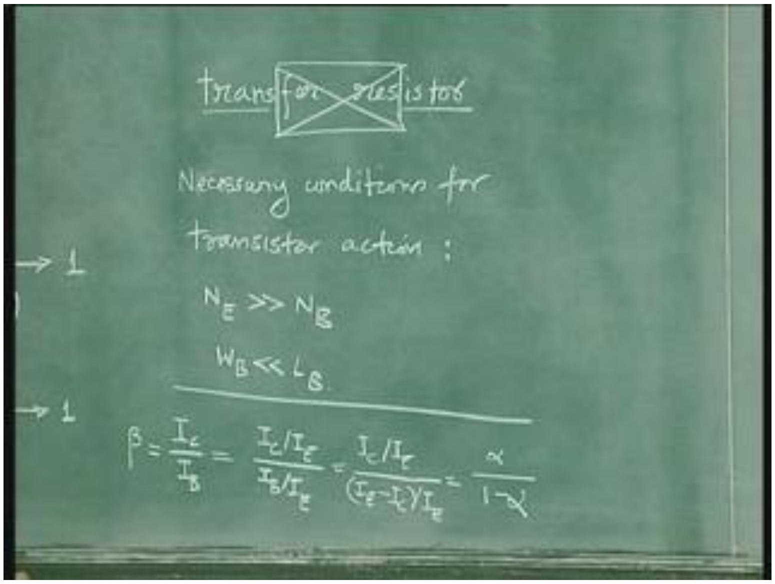


Now if alpha is very close to 1 you can see beta is very large. Now having discussed the situation for collector base voltage is equal to 0 let us see what will happen is you apply a bias between the collector and base regions. Here we have assumed that the collector and base were shorted. Now you want to introduce a power supply here and see the effects of this power supply which can either cross a forward bias across the junction or a reverse bias. So let us start with the effect of the forward bias. It is shown here as the collector to base junction is forward bias and we are increasing the forward bias from 0 onwards so what will happen.

Now we will assume that the base width is very small because that is the condition in a practical device so that almost the entire emitter current is transfer to the collector. So, $W_B$ by $L_B$ is much less than 1 and we will keep the emitter base voltage constant. What happens as you increase the collector base forward bias? So for collector base zero bias your excess carrier concentrations would be something like this. This is close to a straight line, this is delta $P_E$ and this is delta $N_E$ on this side and this is for collector base voltage equal to 0. If your collector base voltage is now positive or there is a forward bias you will have the following situation.

The boundary value of the excess carrier concentration will increase on either side of the junction so your hole concentration on the n-side has increase and you are also going to have excess electrons on the p-side. Since doping in the collector is lower than doping in the base your excess carrier concentration of electrons in the collector will be more. So this is the kind of situation for forward bias across the collector base junction. This is $V_{CB}$ is equal to 0 and these two correspond to $V_{CB}$ greater than 0. Now for $V_{CB}$ is equal to 0 this was the flow diagram. There were no electrons in the collector and there was no electron current. But now you can see from here that $I_{Cp}$ exists because you do have a slope of holes at this junction even for collector base forward bias. But in addition, you also have $I_{Cn}$ because the electron concentration also is raised. Now the current because of electrons is related to the initial slope of this carrier distribution.

Now what is interesting is that this means that the electrons are also injected from base to collector like holes are injected from base to collector as shown by this slope here and this slope here shows electrons are injected also from base to collector in the same direction. So the electrons are also moving in this same direction as the collector current. Now what will happen to this electron current is that obviously it will recombine in the collector with the holes. If you have electrons moving in the same direction of holes then the electron current will be opposite to the direction of hole current because electron current is opposite to the direction of flow of electrons. So you can see from here that the electron current is subtracting from this hole current so this current is subtracting from this current and as a result your collector current is actually falling when you have a forward bias applied so this is your $I_{Cn}$. As you increase the forward bias this component will be going on increasing exponentially with respect to the voltage because the boundary value of excess carrier concentration rises exponentially with respect to the forward bias.

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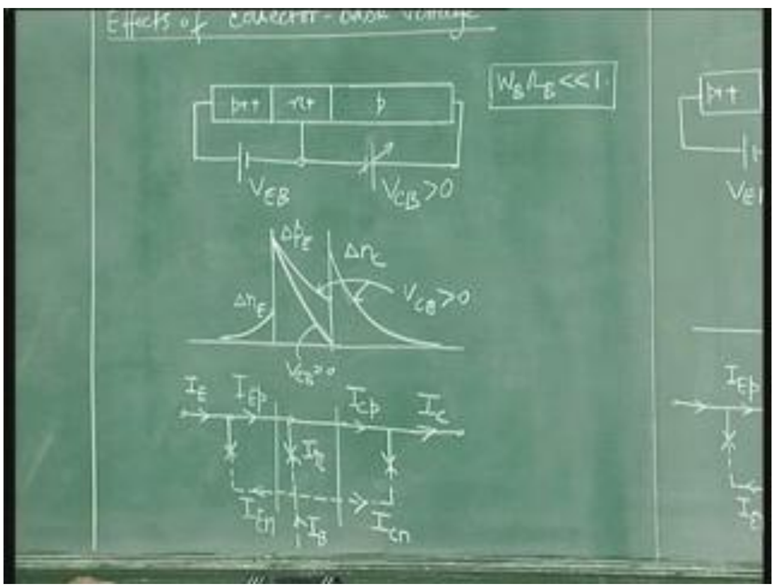


That is really a bad situation because rapidly as you increase the forward bias this current will start increasing and therefore it will subtract from this particular hole current which is injected and your collector current will start falling. You can have a situation where the collector current becomes 0 and it even becomes negative. That means the collector current in this direction is reducing, it is becoming 0 and the collector current may start flowing into the collector. Therefore the forward bias destroys the transistor action. It destroys the transfer of current from emitter to collector which is this particular phenomenon. So, forward bias across the collector base junction is not really beneficial for the transistor action.

We can show this here when you keep $V_{EB}$ constant and for very small base width which is the practical situation in the transistor. As you increase your collector base forward bias what happens is $I_{Ep}$ is dependent on the slope of this particular distribution at the emitter junction so this $I_{Ep}$ is falling. We can see that the slope is falling as your excess carrier concentration starts rising near the collector base junction so $I_{Ep}$ falls and therefore $I_E$ also falls.

Now $I_C$ is $I_{Cp}$ plus $I_{Cn}$ but $I_{Cn}$ is negative in polarity. So $I_{Cn}$ is in opposite direction to $I_{Cp}$. The flow of electrons and holes in the same direction means their currents cancel so $I_{Cp}$ plus $I_{Cn}$ is nothing but $I_{Cp}$ minus modulus of $I_{Cn}$. So what is happening to $I_{Cp}$? Here this is falling, you can see from here that this current falls, you can see this slope is reducing, this slope is more, this slope is less as you increase the forward bias. So $I_{Cp}$ falls whereas magnitude of $I_{Cn}$ rises with a raise in magnitude. So $I_{Cp}$ is falling and this magnitude of $I_{Cn}$ is rising so the difference is really falling. That is why $I_C$ can become 0 and it can become negative also because this quantity can become more than this quantity.

What happens to $I_B$? You can see from here that the area under this curve is going on increasing, the area under the excess distribution in the base is going on increasing so $I_r$ is going to increase. And the base current now is not simply $I_r$ plus $I_{En}$ which was a situation for collector base voltage equal to 0. You also have another component here that is plus $I_{Cn}$ modulus because you can see from here that base is now also supplying electrons to the collector so your base current as increased tremendously. It is this current plus this current plus this current as shown here. So $I_{En}$ is constant but this $I_{Cn}$ is increasing so $I_B$ increases whereas $I_C$ falls. So, each of these things are undesirable. The transistor action is destroyed if you have forward bias across the collector base junction so this not desirable.

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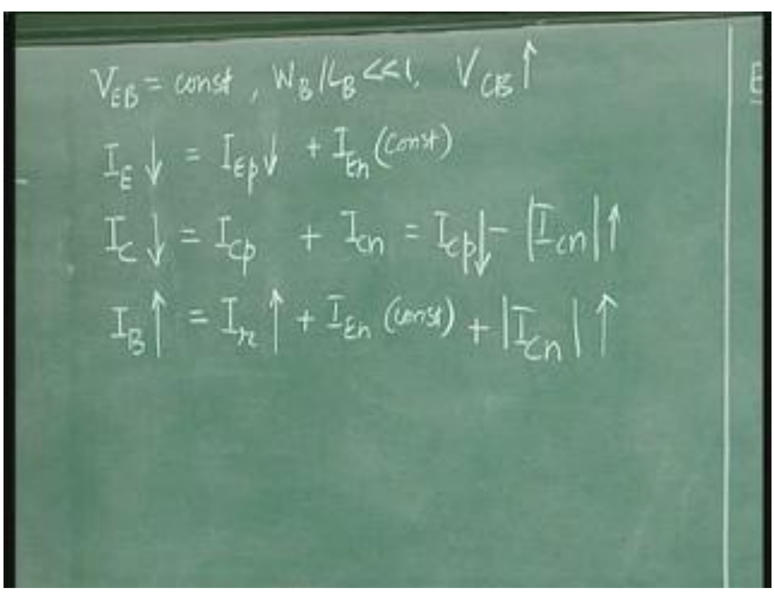

Now let us see whether a reverse bias is acceptable, what happens if you have reverse bias. This is what you shown here, collector base junction has a voltage less than 0. Now when you increase a reverse bias the depletion width goes on increasing and its effect needs to be considered because a part of the depletion region is in the base and a change in the depletion region would mean a change in the base width. Now for simplicity we have not shown the emitter base depletion region which is also there. But this depletion region will be more significant compared to this obviously because this is reverse bias and it can go on increasing whereas your forward bias cannot change very much. So the depletion region here will not change much and that is why it is not shown. So the electrical base width which is this will go on changing as you change your reverse bias so that is one of the effects but then we have to see whether it affects the transistor action.

So let us plot the excess carrier concentration for collector base reverse bias which will be as follows: so this is a depletion edge so here you will have a small negative excess carrier concentration equal to the minority carrier concentration because there is a reverse bias. We will assume that this $V_{CB}$ is greater than three times $V_t$. So reverse bias is more than three times $V_t$ so the excess carrier concentration saturates at negative value. And here similarly you have like this where this is the excess carrier concentration saturating at minority carrier. The magnitude is minority carrier concentration and since doping here is less than doping here this value is more than this because minority carrier concentration collector is more than in base. So this is delta $p_E$, this is delta $n_E$, this is minus delta $N_C$ and this is nothing but we can write this as minus electron concentration in the collector so it is $n_{p0}$ where this corresponds to collector and this is minus $p_{n0}$ corresponds to base and they are really small.

In fact if you show to scale you cannot really show this value because this will be much more than this and this is a linear scale. So what is the result of this? The result is that there is a small current here $I_{Cn}$ but it is in the opposite direction to what it was when there was a forward bias. In forward bias the electron current was injected from base to collector but for reverse bias it is the other way round. This is clearly evident from this slope, this slope indicates that you have flow of electrons like this so this is really a generation current but this current will be small because it is only dependent on the minority carrier concentration and it saturates.

The reverse current across a diode saturates if you neglect the generation within the depletion layer of that junction. This is so called $I_{Cn}$ and now we will show this by the symbol $I_{CO}$ which is the commonly used symbol for the reverse current across the collector base junction of the bipolar transistor. $I_{Cp}$ is not significantly affected because this point is no different from this point which was the situation for zero collector base voltage. So this is not very different except that it has shifted a little bit on this side because of the change in the base width. What you find is $I_{Cp}$ is not affected very much as compared to zero bias. And $I_{Cn}$ which is this component which has come in is really very very small because it is a reverse current of a diode. So in effect what we can say is that the collector current is not significantly affected by the presence of reverse bias. Now, if the reverse bias is very large of course this junction can breakdown.

But so long as we do not go to such have voltages we find that the transistor action is essentially remaining unaffected. The only difference is that there is a small additional current in the collector that is a reverse saturation current of the collector base junction in addition to the situation we had for zero bias. So, all that is happening is we can write $I_C$ is equal to $I_{Cp}$ plus $I_{Cn}$ and $I_{Cp}$ is no different from what we had in the zero bias so $I_C$ is nothing but alpha times $I_E$ and under zero bias $I_{Cp}$ was alpha times $I_E$ and plus this $I_{Cn}$ now is $I_{CO}$ which is the symbol for $I_{Cn}$ normally used.

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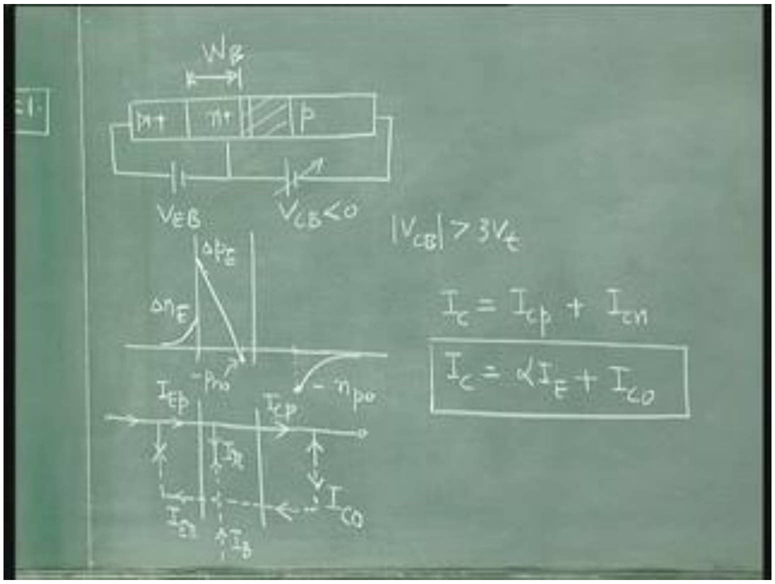


Now the current across this reverse bias junction will also be due to some small amount of holes on this side, this is shown by the fact that this hole concentration has reduced a little bit. But we can neglect this effect because minority carrier concentration on the collector is much more than that in the base so we neglect that effect.

We can write $I_C$ is equal to alpha times $I_E$ plus $I_{CO}$ for reverse bias across the collector base junction. So, reverse bias across collector base junction is acceptable so long as it does not lead to breakdown. Now with that we complete the basics of transistor action in which what we have shown is that zero bias across the collector base junction and forward bias across the emitter base junction leads to a transfer of current from the emitter to the collector and this transfer is almost complete. And if you change the collector base junction bias to forward from zero bias the transistor action is destroyed. But if you change it to reverse bias so long as a reverse bias is below breakdown transistor action remains essentially unaffected. We will now continue with other aspects of transistor action in the next class.