Microelectronics: Devices to Circuits
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Lecture No 02
BIPOLAR JUNCTION TRANSISTER: MODES OF OPERATION-1.

Welcome back to the NPTEL online certification course on Microelectronics: Devices to Circuits. In our previous lecture we had understood the basic structure and the doping profile of a BJT. We have also understood two types of BJT which is available to us. One is known as NPN and other one is known as PNP. In the first case which is NPN, electron is the majority current carrier, in the second case holes are the majority current carriers.

What we will learn in this module or in this lecture is the working principles of BJT, right. And we will see why is it therefore termed as a bipolar technology. Let us may be it will be easy if we start with an NPN transistor and then we can take up the case of a PNP transistor. So before we move forward and we discuss about NPN and PNP transistors let us just recapitulate what we know about PN junction or PN junction diode or simple PN junction right.

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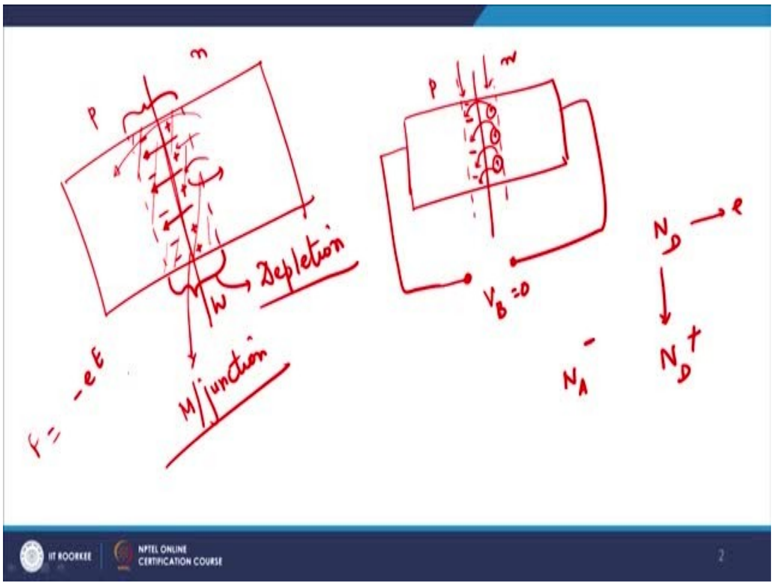

So if you have P type material and N type material here and you do not apply any bias, let us suppose the bias is 0, so I am just keeping it open circuit over here. So V_B is equals to 0 then what will happen is that free electronics from here will be jumping to this place they will be diffusing, right, because there will be diffusion at this place. Why there will be diffusion?

Because you have a large free electron concentration here and you have got very low free electron concentration here therefore electrons will be jumping from N side to P side as a result what will happen is, on the N side you will be left with what positive ions which are nothing but your donor species. And what happens on the P side, these electrons will recombine with holes and you will have negative charges, effective negative charges will be available to you, right.

So, what is the big picture therefore, that even if you do not apply any bias because of a diffusion between P type and N type material you will have a region near its junction, this is known as the known as metallurgical junction, right? Please understand this is known as a metallurgical junction, this junction, PN junction is basically known as a metallurgical junction.

If you look at this junction so initially therefore what will happen is that electrons will be moving and this side you will have fixed charges which are positive in nature and you will have fixed charges which are negative in nature. Why, because electrons have left from the from the negative side as they went they left behind their donor atoms there and therefore you will have this positive charge. So, what happens is that? There will be electric field which will be directed from N side to P side inside this region, right.

First of all, therefore, this region which you see is referred to as the depletion region, right. So this is the depletion region, so why it is known as depletion region? Because this is the region which is basically depleted of any free charge carriers, so please understand there are charges but these are not free charges, they are fixed charges, right? Why fixed charges? Because electrons have left their position leaving their donor atoms ionised donor atoms.

So, if I have a donor atom N_D, right, it gives one electron and it converts itself to N_D^+ right, accepts that atom right, gives one holes there and becomes negative atom available to us. Now, So the idea therefore is that since this is and therefore this region which you see in front of you this region is primarily devoid of any free charge carriers and therefore it is known as the depletion region which means that under zero, even under zero bias condition the PN junction is basically having a depletion width which is W let us suppose right, this will always be there you like it or not at even at zero bias there will be the junction will be deployed or devoid of any free charge carriers.

Now why after sometimes this movement stops so the free electron from N type to P type. So what is happening is, therefore, for electron to move from N type material to P type material now it has to cross this depletion region, agreed? But as just as it enters this depletion region it sees an electric field which is directed this side which means that, because if you remember it is -E into E right, negative why (mine) because electron is in negative charge therefore, the force on the electron is -E into E and therefore electron trying to enter this side will be pushed back on this side right.

So, beyond a particular time when the electric field becomes so large that any extra electron coming from N type and trying to enter into the depletion width to go towards the P side will be pushed by the electric field within the depletion region and force it to move outside the depletion region and throw it towards the N side. So what is the overall picture therefore what we get?

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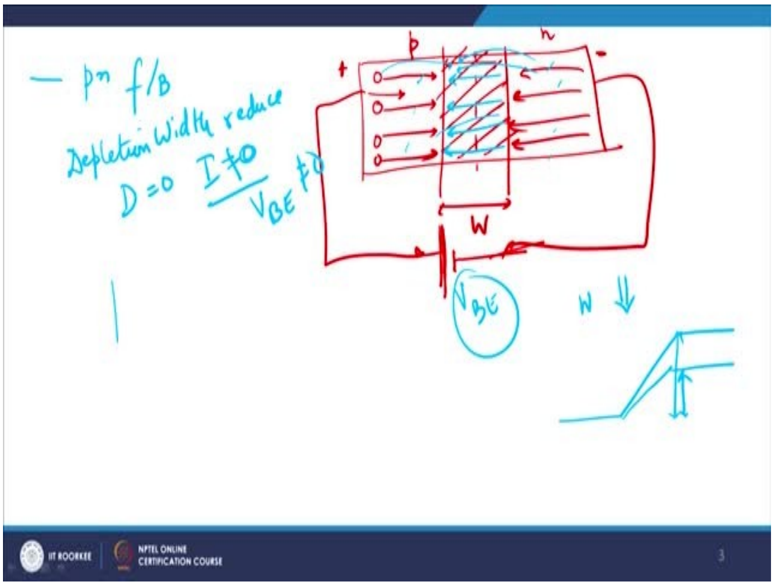

That overall picture therefore is under zero bias condition your there will be a fixed width of a PN junction and that fixed width is basically my depletion width W right and therefore, this will be devoid of any, this part will be devoid of any free charge carriers. Right if this is the PN junction diode and we have not applied bias here. Now, let us see what will happen if we forward bias this PN junction as we very well know forward bias basically means the P type is connected to a positive terminal and N type is connected to negative terminal fine. Let us look from an N type material.

Now what will happen is that or from the P type material either way you can have a look from the P type material. So if you have a positive polarity battery connected to the P type material here, the holes which are majority current carriers here will see an electric field in this direction because this is positive and this is negative, so there will be electric fields. So these holes will be pushed towards this region, right? It will be pushed.

Similarly electrons will be pushed in this region right? They will be pushed near the depletion edge as it enters. So please understand, within the depletion region the electric field is in this direction so I will make the highlighter pen slightly change the colour so that you are able to appreciate what I am trying to say. The electric field within the depletion region is in this direction whereas outside it is this one right, this is the direction.

Therefore, once the hole enters a depletion region, let us suppose this is the hole, it enters the depletion region by virtue of this electric field. It will be again thrown, it will be at least, these electric fields which are marked in blue will try to throw the hole towards the P side and any electron entering from N side will be thrown towards N side. But now, please understand, you have an external bias which is say V_{BE} let us suppose base emitter or whatever V_{BE} or V_{XE} whatever, which will help the holes and electrons to cross this barrier right.

So, if so if I am able to see that so extra electrons will be crossing this barrier or extra holes will be crossing this barrier and once it reaches on this side right it tries to remove some of the electrons available here and therefore what happens similarly electrons moving from this side to this side as it starts to move the depletion width actually therefore starts to reduce, right. So as you make the PN junction more and more forward bias your depletion width starts to become lower and lower this can be also understood in this manner.

So if you look at the depletion width it primarily means the holes has to acquire an extra energy to cross this barrier so for an hole it is basically a barrier right. So if you are able to provide a bias which is V_{BE} what happens to the holes is that it lowers the effective barrier drastically, so this was the initial barrier length, now this becomes the initial barrier.

Now it is easier for holes to cross the barrier right so we should look it in this manner so we come to one major conclusion out of it is that when your PN junction is forward biased right, the depletion width will reduced, a time might come when the depletion width will go to 0 and you will have some current flowing because of the external bias for V_{BE} not equal to 0.

So, there will be some current not equals to 0 for V_{BE} not equal to 0. This is the condition when you do forward this is known as forward bias.

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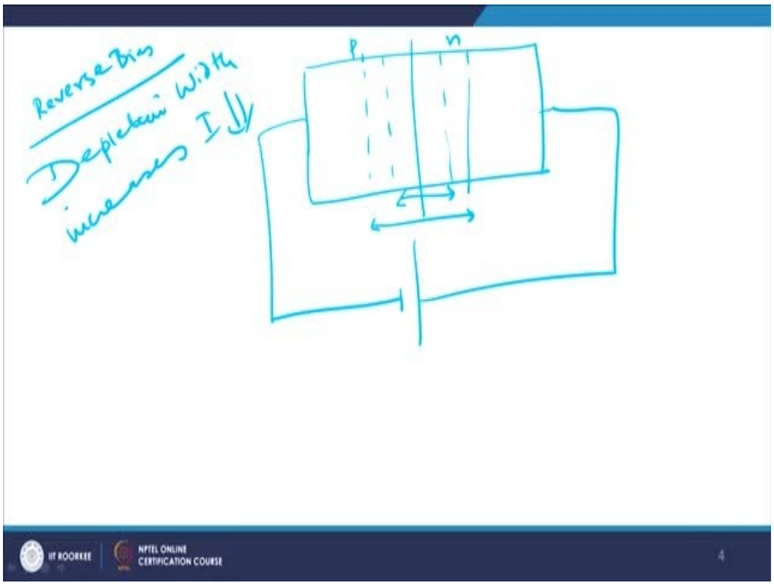

Now, let us look at the fact what will happen if you go to reverse biased, which means that you just convert this whole thing and may be the next I can help in this slide. Let me say that I have this and I have got this PN, I had a depletion region already formed side now I had connected P type to a negative and N side to a positive side. So I just reversed the polarity of the battery right.

Now, I leave an exercise to you to and you can easily appreciate what will happen now is that this depletion width which was initially this do this will now become larger, will become larger. The new value of the depletion width will be this one, which means that under reverse bias condition, reverse bias condition the depletion width, depletion width increases, width increases, right, and as a result the current will be further lowered or there will be no current flow.

So, please understand therefore so from a basic study of PN junction diode theory or PN junction theory, when you forward bias a junction more is the current, when you reverse bias a junction less is the current. Why, because the forward bias will give you a lower depletion width and reversed bias will give you a higher depletion width. With this knowledge you have gained as far as a simple PN junction is there let me come back to NPN transistor explain to you how a NPN transistor works.

So, look at the fact, let us remember our previous lectures basic principles that the emitter will have a very heavily doped, your base will be relatively very less doped, it will be very thin also and your collector will be relatively less doped but it will be same doping as that of the emitter.

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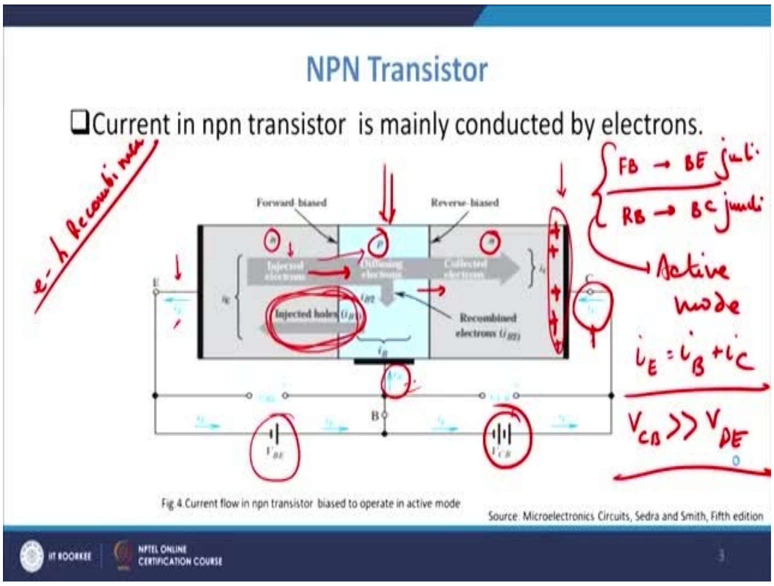

So this is an NPN if you look very carefully this is N, N type semiconductor this is again an N type semiconductor and this is P type semiconductor. What we have done is we have forward biased the base emitter junction. And what we have also done is we have reverse biased the base collector junction right this is just for information at this stage, this is also known as the active mode of operation. We will discuss that in subsequent slides, but just to give you a functionality of this NPN transistor, we forward biased the base emitter and reverse biased the base collector and see how the current flows.

If you look very carefully therefore, when you forward bias the base emitter junction right, you reduce the depletion width on the base emitter junction region as we discussed just few minutes back, right and you reduce it. When you reduce it you force large number of electrons from the emitter side and they will be injected on to the base side. So this is the injected electron which is flowing right, because you have forward biased N and P junction here, right. As it enters the base region this is what is the critical aspect of a bipolar technology bipolar junction transistor works.

As it enters the depletion region here right, please understand, the base region is typically very having very small number of holes because it is slowly doped and it is very thin. So what will happen is majority of the electrons will actually cross the base very fast because it has very high velocity, but some of the electrons will actually combine with some of the holes present here. So there will be an electron hole recombination right, so the holes will be lost because electrons will eat into the holes and as a result the holes will be lost, right.

In order to make the same number of holes as it was previously you see there will be a current that is known as I_B which will be flowing into the base, so please understand this blue coloured current source which we are showing to you is basically the conventional current these are not the electronic current right. So, therefore, if you look at the base here which is this one if you look at the base here then in the base the direction of the current is basically into the base and the reason why it is into the base is that the holes are now.

So, let us suppose 10 electrons recombine with 10 holes, so 10 holes were lost in order to therefore make again the 10 holes available to me 10 holes from the base side which is being fed by V_{BE}, what V_{BE} this V_{BE} will enter into the base side and therefore, the blue coloured arrow is going inside the base right and this is the base current, very-very small current because why base current is very-very small, because the number of holes are very-very small, right. So the probability of recombination is also very-very small and therefore I would not expect large base current to be available to me.

Now, what has happened therefore is, those electrons which did not recombine they went and towards the base collector junction. But please understand base collector was reverse biased right so when the electrons come here what does it sees? It sees a negative potential here, sorry it sees a positive potential here, I am sorry, because of this V_{CB} and therefore, they will rush through the depletion region, right and go towards the collector side. If there would not have been any positive charge here or positive potential here electrons could not have cross the base collector barrier because base collector barrier please understand is large as compared to base emitter because it is reversed biased.

So, if there would not have been any positive potential near the collector end I would not expected to see the electrons to cross the barrier because you are not providing that much amount of energy to electrons to cross the barrier and that is reason what will happen the electrons would not flow. But since you have provided a V_{CB}, a very large potential as compared to V_{BE} and that too reverse biasing the base collector, the electrons will see a very large potential on the collector side and as a result what will happen it will force itself through the depletion region and reach the collector side right.

And as a result there will be a collector current as you can see it is again pointing inwards why pointing inwards? You very well understand why is it pointing inwards because the electrons moving outwards therefore hole current is moving inwards. So, I have I_B inwards I_C inwards and I_E also moving outwards right, I_E outwards because electron currents is moving inwards right, so this is what is basic structure of base current looks like or the basic idea looks like.

Now, if you look at another issue here which is quite an interesting issue is that when you apply a V_{BE} base emitter you are basically forward biasing this base emitter junction right. Base emitter junction you are forward biasing it. Now, when you are forward biasing it, you are also reducing width of the emitter base junction layer as we have already discussed this point. So, just as it is easier for the electrons to move towards the base side it is also easy for the holes to move from base towards the N side.

So, you see you will also have one current contribution because of the injected hole from the base side right, so you have injected electrons this is primarily diffusion and then you have drift and these are injected holes from base towards the collector side. However, as $I_{B\,1}$, $I_{B\,1}$ will be very-very small because as I discussed with you small base current is there and therefore $I_{B\,1}$ will be relatively very small which is there with you, right. So, I have three currents therefore, I_E which is here right, I_B and I_C and therefore, by Kirchhoff's current law I_E will be equal to $I_B + I_C$, right.

And obviously V_{CB} should be much larger than V_{BE}, fine. And this is the basic fundamental working which means that if 100 electrons started from the emitter there maybe 90 electrons reached towards the collector 10 were recombined in the base and therefore by changing the biasing of the base emitter junction I can change the total amount of current flowing through the collector side, right.

I can also therefore change the collector current by changing the base current because $I_E = I_B + I_C$ so if I want to make I_C larger I reduce my I_B because I_E is fixed. So changing one current or getting the final current high or low by changing one of the parameters of the other current is the prime example of a BJT. That is the basic example of a BJT which I just wanted to give you an idea.

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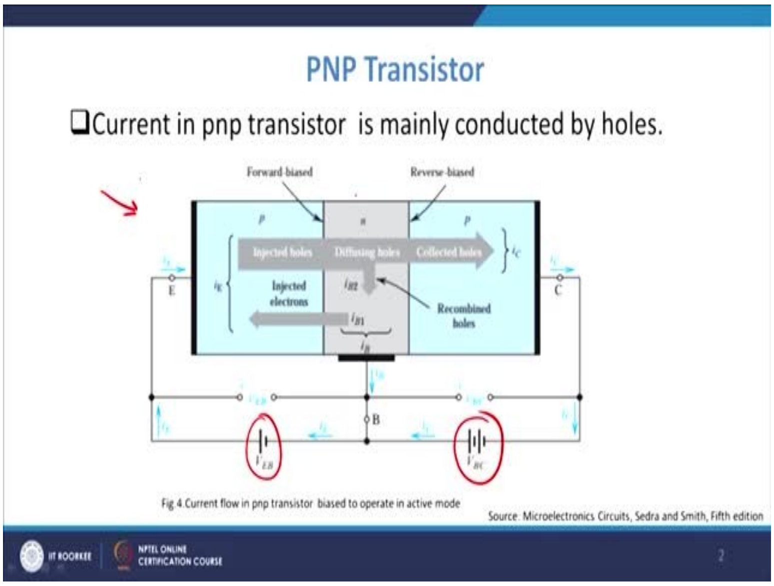

The same concept the same thing exactly the same thing can be applied to holes also. Only in this case the biasing of the battery will change and this is therefore forward biasing it because it is P and N type and this is V_{BC} again reverse biasing it. Understanding part is exactly the same as the previous case so I am not going into detail of this you please work it out yourself from the book or you can yourself do it, it is pretty easy and pretty simple to understand. Concept remains that same the base emitter will be still forward biased, depletion width will be small. Base collector will be reversed biased it will be still large and so on and so forth.

In this case since the base is made up of N type material the recombination on the base side will be relatively small and therefore, the base current will be less relatively very small right. And in the second case as you increase the value of V_{BC} or V_{EB} you will be actually able to control the current flowing through the collector side. So, these are the few important aspects which one should be able to handle as far as this is concerned.

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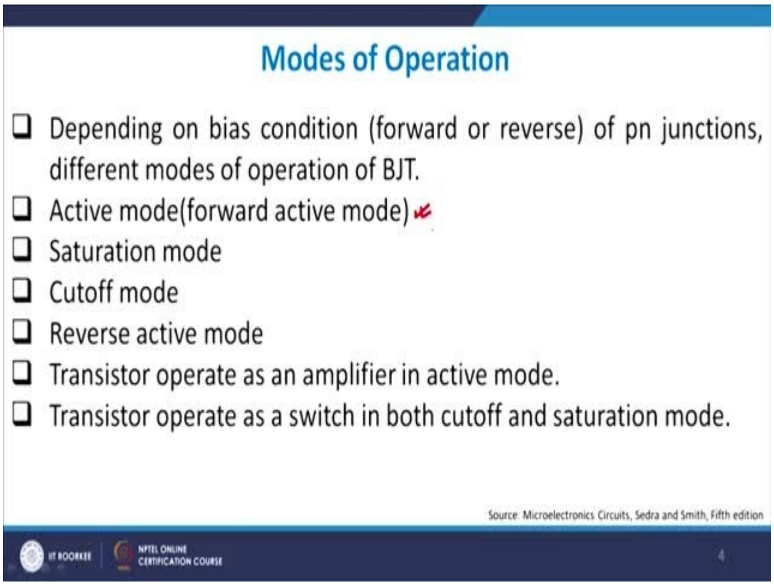

Now, therefore the various modes of operation are given as these are the various modes of operation right, depending upon the bias condition very simple straight forward. So there are two biases right, so I can have 2^2, so I can have four sort of modes right.

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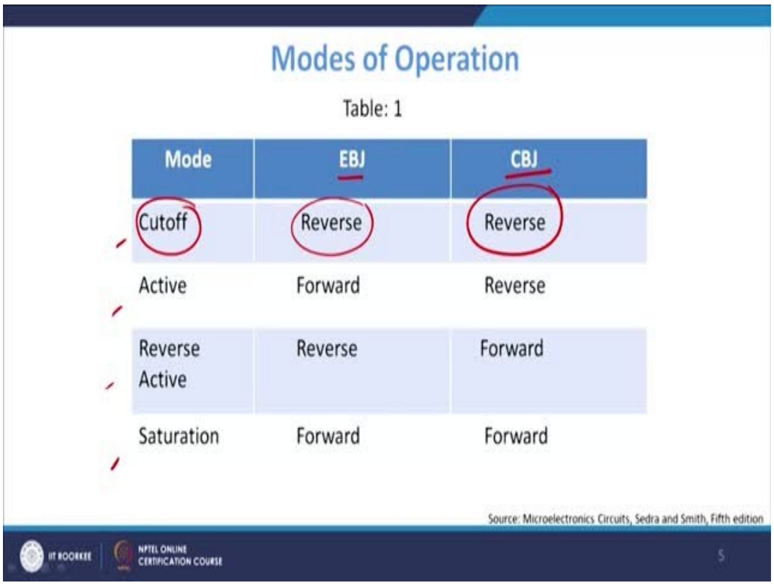

Is it okay? Why, because there are two bias conditions, right and I can therefore, have and each one of them can be reversed, right because why two biases two battery sources and each battery source can be either forward biased or reversed biased. So, I can have therefore four conditions available to me forward-forward, forward-reverse, reverse-reverse and reverse-forward. So, each one of them will give rise to each methodology. We will come to it one by one and we will see how it works out. I think you can appreciate these points.

The first thing is if both emitter base junction this is EBJ and CBJ is the collector base junction. So if EBJ is reversed and CBJ is reversed then, of course, you can understand it will be cut-off why. Why it will be cut-off? The reason being is both a reverse biased then emitter base junction depletion width is also very large, right and collector based junction width is also very large.

Both the widths are very large, so there is no question or no probability of any electron coming from the emitter side and entering into the base side, right and therefore, there will be very-very small current or almost zero current in the region, then we define that to be as cut-off, right. Why cut-off, because you are applying a bias but you are not getting any output current, then we define that to be as cut-off mode of operation. I just missed one small point in the previous discussion which I will just take care of it by this understanding.

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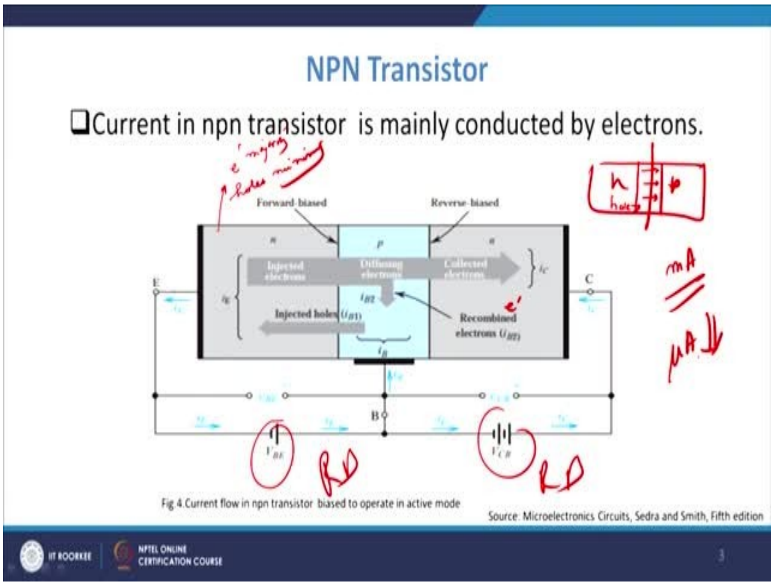

That is something like this, see in an N type semiconductor which you see in front of you this one N type. Electrons are the majority carriers right, this we have already seen majority carriers but we forgot one small thing that the holes are also there but these are minority, very small in numbers. So on emitter side you will have electrons as well as holes, electrons will be very large in numbers and therefore, we were discussing the current flow in a BJT from electron point of view but there will be also holes available here, please keep this in mind.

But, for example, in this case even if there are few holes inside this N type semiconductor and you forward bias this emitter base junction which is available. Please understand for a minority current carrier it will not be a hill but a slope. Why it will be a slope? Because this is emitter base junction so if it is N, basically it is a PN junction. It is an N and P so this is therefore the electric, the electric field will be, these are electrons, electrons will move the side and electric field will be directed in this direction.

So, any hole which enter somehow other than the depletion region can be dragged, so for hole it is not a big hump, for hole it is basically a small slope. Similarly, electrons on this side will be also a small slope as you move. So please understand though majority current carriers do not contribute to the current when both are cut-off which means that when both V_{BE} and V_{CB} are reverse biased RB-RB then we define it to be cut-off, but please understand this is by virtue of the fact by which cut-off because majority of the current carriers are very low or almost zero.

But please understand there might be a current because of the minority current carrier because for minority current carrier it is not a hill but a hump going downwards, right. But since, that current is very-very low may be ten or hundred orders lower than the actual current, so if you have milliampere current flowing for the forward bias or on current this might be of the order of microampere or much smaller than that, we generally neglect that current and say that okay the device is off.

But please keep in mind that as a second order effect, you generally have these currents which are there with us by virtue of minority current carriers, they are always there that makes our life slightly difficult. So, we understood cut-off so cut-off is what when both my emitter base as well as collector base junctions are reverse biased and you therefore, understand why they are reverse biased.

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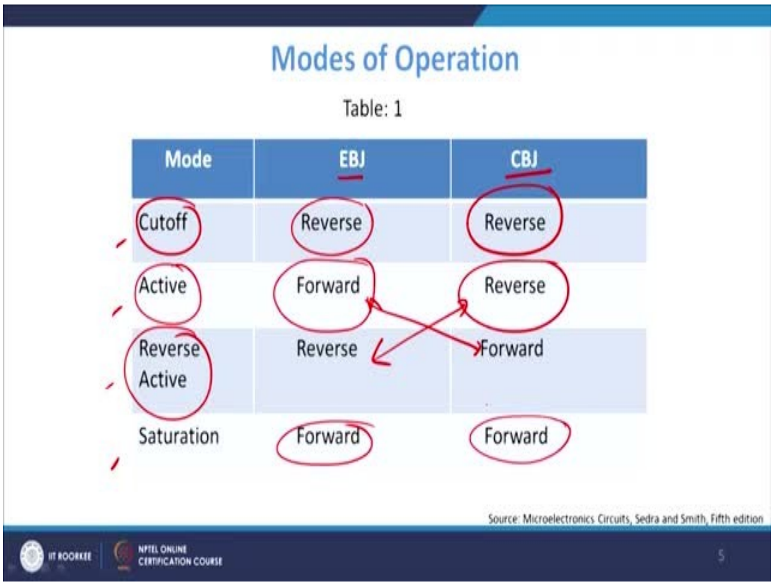

The second is basically my active mode of operation and this is the most actively use mode of operation generally used in amplifiers to a larger extent, where your emitter base junction is forward biased but your base collector junction is reverse biased, please understand the idea behind it. When I have emitter base junction as forward biased you are allowing larger number of emitter atoms which is electrons, emitter free charge carriers to enter into the base region to collector region, right. So currents are very-very large so when you reverse biased a collector region you actually allow large amount of, you allow acceptance of large number of electrons from the emitter side, right.

So, therefore, in the active region emitter base is always forward biased and collector base is always reverse biased, right. Let us look at reverse active, reverse active is when you just reverse these two. That means your emitter base junction is now forward biased and you collector base junction is, oh sorry, your emitter base junction is now reverse biased which means that you do not allow large number of emitter currents to flow but then you make your forward biased collector base junction.

The last one is saturation in which case both emitter as well as collector are forward biased, in this case you have a large amount of current which flows through the because both your collector base junction and emitter base junctions are forward biased. As a result you allow a large number of amount of current to flow. So there are four modes of operation, in general as we move on we will see that I can use transistor as a switch, right, wherein I can move from cut-off to active, active to saturation.

I can also use transistor as an amplifier when I moved from active to reverse active and so on and so forth. So just by varying the biases, right applied biases I can let it works sometimes as a switch from ON to OFF state and vice versa and I can also let it work as an amplifier. So we will see as we move along what these operations are and how these operations looks like, right. We will not give details of this one but I will give a brief idea about where we are at this stage.

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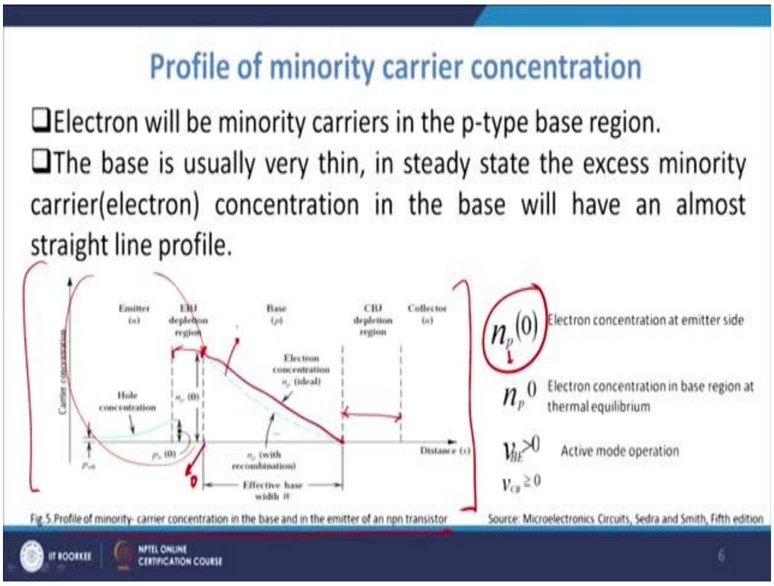

As I was discussing with you that there will always be minority current carriers which will be there apart from majority current carriers in a particular region. Now if you look at this plot, see the plot which you see in front this plot, this is basically a profile of the minority carrier concentration in the base and the emitter of an NPN transistor, so this is my emitter side, this is my emitter base depletion junction. This is the emitter base depletion junction, this is my base region and then this is my collector base depletion junction here.

So, your NPN transistor base is basically P type right. So, what does this graph show is that in ideal condition the electrons concentration which electron is basically a minority current here on the base side will fall linearly from N_{P0}, N_{P0} if you look very carefully N_{P0} means electrons on the P side at zero means this is zero this is zero. So from there it will be maximum because it is nearest to the emitter side and then it will fall to zero near the base at the emitter side. Why, because at the collector side all the electrons are pulled by the virtue of the reverse bias of the base collector junction.

So at the emitter side you have large number of minority current carriers because electrons are being fed from the emitter side. So your NP0 is typically very high. But as you move towards the collector side, since collector is drawing all the electrons away from it I would expect to see per unit volume electron available there to be relatively very low, right. So that is the reason we see a linear, almost a straight line drop of electron concentration from a very high value to almost zero value near this thing.

But we will not go into details of it but with recombination because actually this is with assumption it is the only combination, if there is recombination it is almost a parabolic sort of a non-linear profile which you see in front of you. Not at this stage not very important from the point of view of understanding the physics of the device. But please understand two things that the doping concentration of my minority current carriers in the base region is a function of my width effective base width and so on and so forth, right.

So, this is what the effective base width looks like, may be in the next turn when we come back we will discuss about the various concentration, electron diffusion current and so on and so forth. What we have done in today's lecture is given you an idea about, this thing about how the minority current carrier behave in a P type base region. We have also come to a point how we have, how a PN junction works and therefore, how it can be translated into an NPN and PNP transistor and its functionalities right.

So, we understood all these things, when we meet tomorrow or next time when we meet I will be discussing some mathematics about the current flow in a transistor which is carried off both drift and diffusion and then see how we can optimize the functioning of an NPN and PNP BJT. So, this is what we have learned today and we will hope that you have understood a part of this work as far as this course is concerned. Thank you very much!