Microelectronics: Devices to Circuits
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Module 3: Microelectronics: Devices to Circuits
Lecture 12: BJT Second Order Effects - I

Hello everybody and welcome to the NPTEL online certification course of Microelectronics: Devices to Circuits. In our previous interactions, we have actually looked into BJT as an inverter and we have understood how BJT's inverter can be made using a simple common emitter or emitter grounded BJT. We also seen that the noise margins are not equal. So, basically N_{ML} and N_{MH} are not equal, right? And therefore though it, though therefore a BJT will be a good acceptor of one, it might not be a very good acceptor of zero or receptor of zero right?

So if your low noise margins are typically very low, then even a small noise when you are inserting zero will result in a change in the value of an output voltage. And that is the problem in any of your BJT that your noise margins are relatively not very high and therefore you generally get a noisy reception in the output side. First thing.

Second thing is that typically as I discussed with you, since you have to if you want to use it as a switch, you have to move from saturation to cut-off and vice-versa. And therefore removal of charge carriers from saturation will take some finite amount of time, right? And therefore the time taken to switch from cut-off to saturation and back to cut-off, there is a finite time and therefore you will always have a limitation at which the BJT can work in terms of frequency limitations.

What we will be now looking is basically into bipolar technology's second order effects. Which means that the first order effects were primarily the drift diffusion phenomena which the bipolar technology works and we have also seen the current equation there. We will be now looking at some second order effects, which means that those effects which generally don't rise as such but may become prevalent under certain conditions, right? So under certain conditions they might show their influence on the current voltage characteristics of the device. Otherwise they are quite silent and they don't, they are not so much receptive to variations.

So what we will be looking therefore is, one is the drift in the base region and what people have done now, we would just like to show you what we have done here is that if you look at this equation I_{NX}, which is this one, right? This one.

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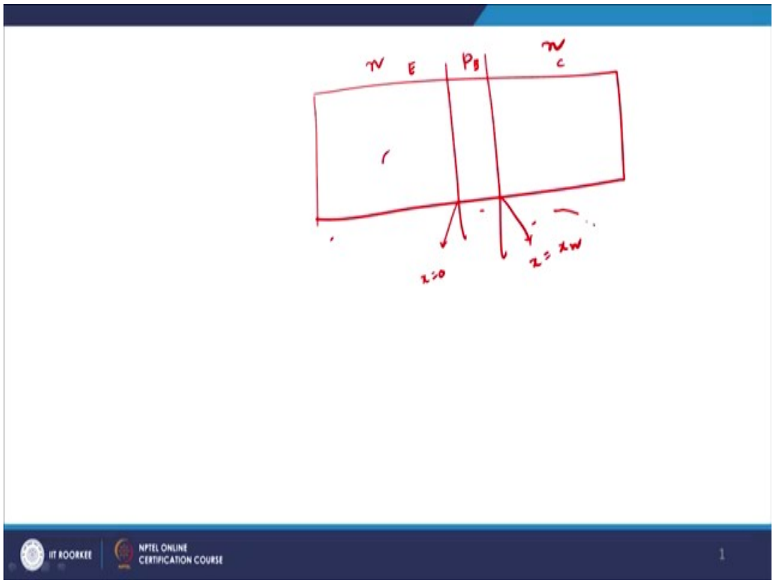

The first part, so this is the total current because of the charge carriers which is there in the region. So I have got NPN transistor right? And within that, as I discussed with you the P region. So I have got NPN. N has got the largest doping, highest area. P has got the minimum doping and minimum area and N has got the, or collector has got the relatively moderate doping.

So what I am trying to tell you is that from this point, let us suppose this accounts to X equals to zero to this point which accounts X equals to say X_n. Then we know that the very, how is the electron profile which is basically the majority current carried in the P type base varies, right? So this is what I wanted to discuss with you in this case.

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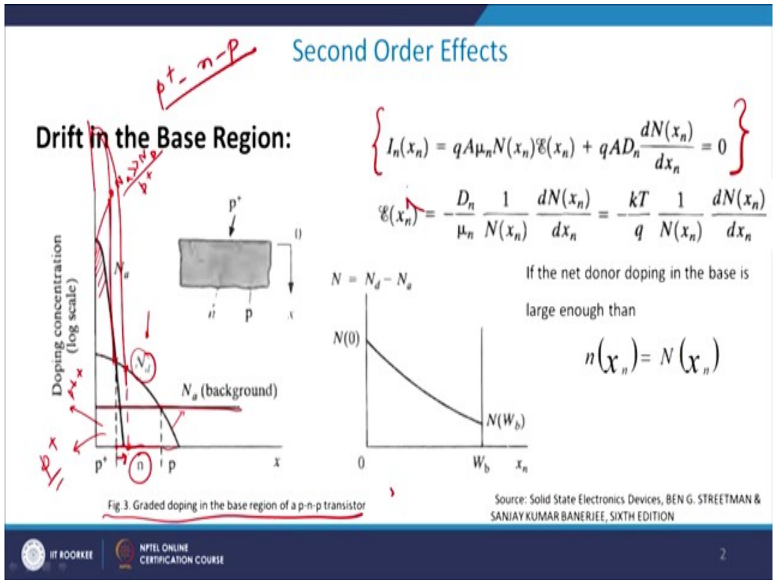

So if you go back to the slide, you can see that. So if you look at this figure 3 which you see, this is basically known as a graded doping and you can see here that what we try to do is that we first make an acceptor grading.

So acceptor background is there. So this background is basically acceptor which means that all of it is basically made as P type, first of all, right? We make it all P type. The whole of it, we make it as P type. And then what we do is that, we then dope it with donor atoms. So this is the donor atom which we are doping with and then we ensure that the donor atoms exceed the acceptor atoms at certain regions which is between this point and this point. And therefore these two points are basically the edge of the base.

So this is my base for a P^+, for a P^+ NP BJT. Since your N_d is larger than N_a at this point and at this point, right? So they are larger in the sense that they are more in value. So I would expect to see a larger donor concentration and therefore this will become more N type as compared to P and that is the reason you get P type here. In this region of course, N_a is therefore larger than N_d. And therefore this is basically a P type.

Since it is very very large, as you can see it is quite large as compared to N_d, we refer to this as a P^+ region because the doping is very very high, right? Similarly, when you reach to this side, your acceptor ion, your dopant N_d, the donor ion actually reduces much below the value of your acceptor ion concentration. And as a result this becomes a P type. So I got a P^+ NP.

So how do you do it? This is also known as a graded junction doping or a graded doping profile. And what we do here is therefore in the graded doping profile, we vary we can control the width of my base as well as of the emitter as well as the collector by simply changing the dopant profile, right? So, doping profile right? That is very simple and easy to do action. You can also change the doping.

For example if you wanted to make this one more P $^+$ type, so you want to make it P $^{++}$ then you simply increase the acceptor ion concentration in this manner. You wanted to shift this line from this side to this side then you need to cut somewhere here. So when you cut the N_a here, the starting value comes out here. So I can do all sorts of manipulation and I am able to achieve a very straight forward methodology of having P $^+$ N.

Now let us suppose your electrons are the majority current carrier, holds are the majority current carriers. Therefore electrons which are there are basically your minority current carriers.

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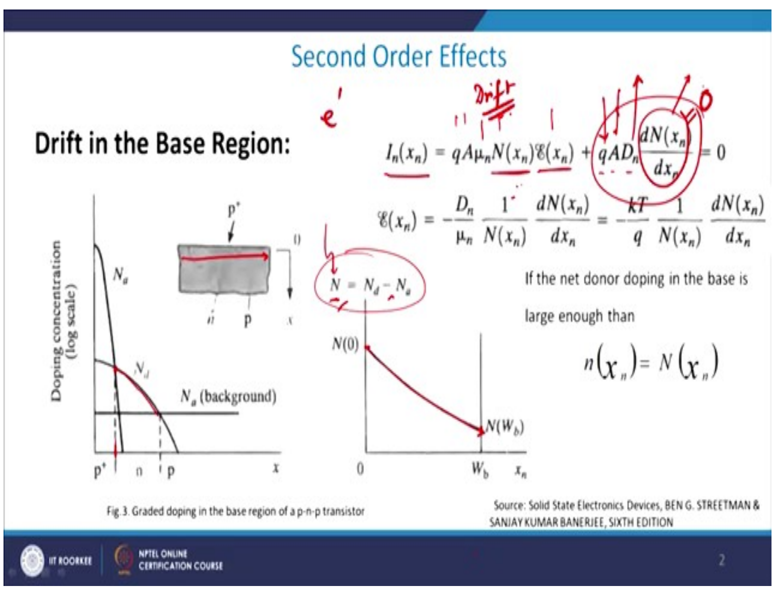

What we are assuming is that let us suppose the effective charge carrier at a particular place is nothing but N_d - N_a right? So you had N_d, let us suppose 10^{15} and N_d was 10^{19} and Na was 10^{15} or 10^{16}. Then you subtract both of them and that is the effective N_a or the effective number of dopant species.

So if we have 100 % ionization, I would expect to see that that many number of free charge carriers, if $N_d > N_a$, free charge carrier is electrons. If $N_a > N_d$, free charge carriers are holes. We will be of course available to you. Now to understand this, let us suppose I have electrons as the majority current carriers. Then I define the current I_n at any point X_n within the circuitry, within the BJT. So this is the value this is the X variation, this is the X variation, is equals to q times A $qA\mu_n N(X_n)E(X_n)$.

I will explain to you what these terms are. N is the charge density, the dopant charge density which you see, E is the electric field from base to the, from the emitter to the base region, E electric field at that particular point, Q is the electronic charge, A is the area of the cross section of the emitter or the base, and μ_n is basically the mobility of the charge carriers, right? So this is basically by virtue of your sort of a drift, a drift current which you see. Right?

Similarly, you will also add a current which is by virtue of diffusion because, please understand that the doping within the base region is not fixed right? It varies because as you can see here, N_d is varying like this. So I would expect to see that at 0 width, at 0 or at when the base starts, the doping concentration is maximum and then it starts to fall down in this fashion, right? And that is what is shown here that I have got maximum width here, maximum number of doping concentration and then it starts to fall down as we move from the edge of the base to the, edge of the emitter to the edge of the collector.

And therefore, we have a diffusion term which is given as qAD_n $dN(X_n)$ $d(X_n)$. Which means that it is the charge again, A is the area right? D is the diffusion constant for electron or a diffusion coefficient for electron. And $dN(X_n)$ $d(X_n)$ is basically meaning the number, how the number of charge carriers are varying within this point. Now please understand if the doping concentration within the base side would have been constant, my this term would have been equals to 0. Constant means independent of the distance the doping is always fixed. So if it is 0, the only contribution would not have, would have been only from the drift component and not from the diffusion component.

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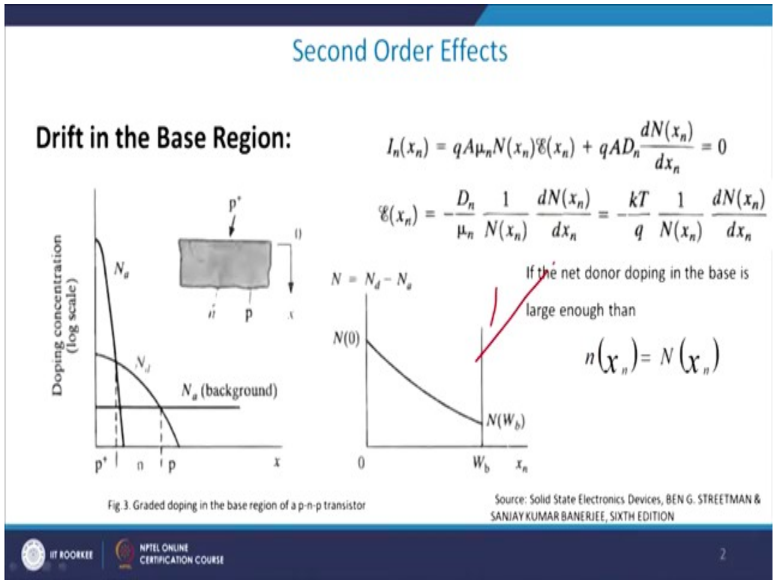

And, all of you can therefore understand that therefore obviously the drift component will have always a component which is primarily proportional to the area as well as to the effective number of charge carriers or number of charge, doping species in that particular point.

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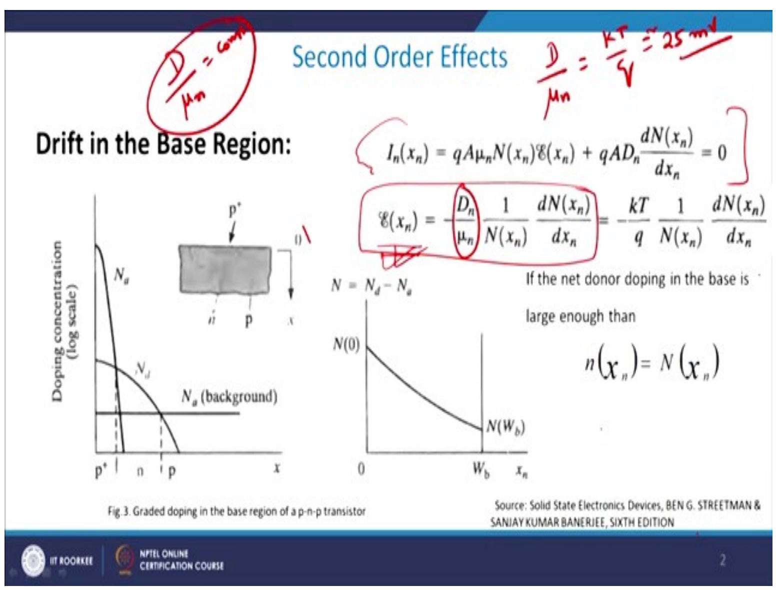

Similarly from Einstein's equation or from otherwise, we can find out that E (X_n) means electric field at any particular point (X_n) is given by this formula, the same formula which we get right? And we can from there we can get the value.

So this is very simple and straight forward. From this equation only, from this equation only I can get this very easily, right? Provided you make the drift current equals to 0. Then I get D_n/μ_n, D_n/μ_n into $1/N_x$ dN (X_n) is equal to – kT/q, right? 1/N (X_n) and d (X_n). Because why it is kT/q because D/μ_n, D/μ_n is equals to kT/q. kT/q is constant at 300 K, approximately 26 millivolt or 25 millivolt. So D/μ_n is always a constant quantity, right? At 300 K, it is a constant quantity.

And therefore we can safely write down this D/μ_n to be a constant and that is equal to – kT/q minus equals to – kT/q upon 1/N (X_n) dN (nx) dx. Therefore the total electric field at any particular point E (X_n) will be a strong function of how the diffusion species is varying with respect to space right? That is very important which you see here. It will also depend upon the number of dopant species available at a particular point X_n within the network.

If that is very large, the electric field, the absolute value of the electric field will be fall, right? Will be falling down. So we have understood therefore that in the base region if there is a small amount of change in the value of N_d, I will have the drift in the base region. Therefore there will be a drift carrier, there will be a drift, electron will be drifted through the base region right? And that is quite an interesting phenomena which people see.

So as you can see there is a fairly sharp discontinuity in the doping profile, right? Your doping profile shows a sharp discontinuity. Which means that since the doping, and the reason being that since there is a certain change at the interface between N_d and N_a, right? And therefore there is a sharp change.

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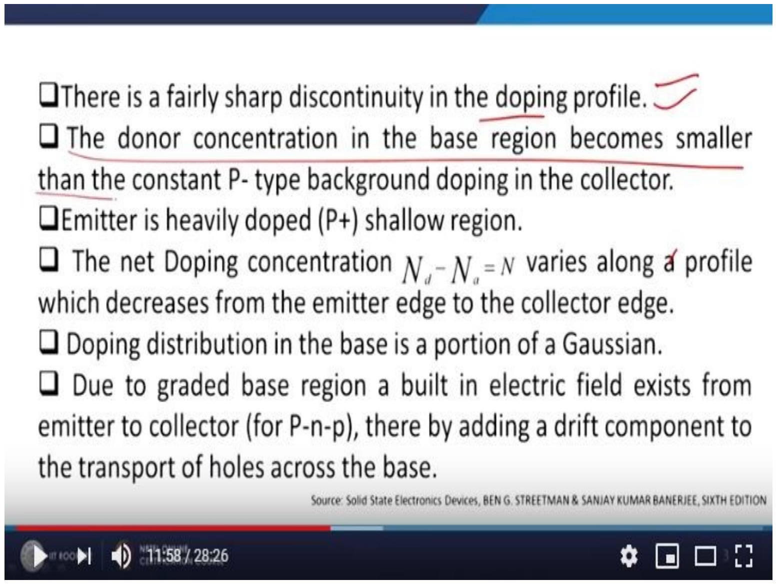

So as you can see the donor concentration in the base region becomes smaller than the constant P-type background doping in the collector. That we have already discussed in our previous slide, we have already discussed that the donor concentration in the base region, right?

So if you remember the previous discussion was, the previous discussion if you look, this is P^+NP right? This is P^+ N and P. So what I am trying to tell you is that the donor concentration, the base region becomes smaller as compared to the collector concentration on the collector side.

So on the collector side you still have P but on the base side, since donor is slightly higher, you get N region available to you. And as you can see emitter is heavily doped shallow region, it is a heavily doped region. Why? Because the acceptor concentration is much much larger as compared to the donor concentration there. Now the net doping concentration N_d - N_a varies along a profile which decreases from emitter edge to the collector edge. This we again discussed. Why? The reason being very simple that if you look very carefully, the N_d is falling from this edge to this edge, right?

And since it is N_d - N_a, right? So since Na is constant at this stage, I would expect that the profiling here will also be between this point and this point, right? Parallel to this line, right. Fine? And that is what you get. That it is varying, it is maximum at the emitter edge and minimum at the collector edge, right? Doping distribution in the base is basically can be simulated using Gaussian.

Gaussian functions or a Gaussian doping concentration is something that looks like this.

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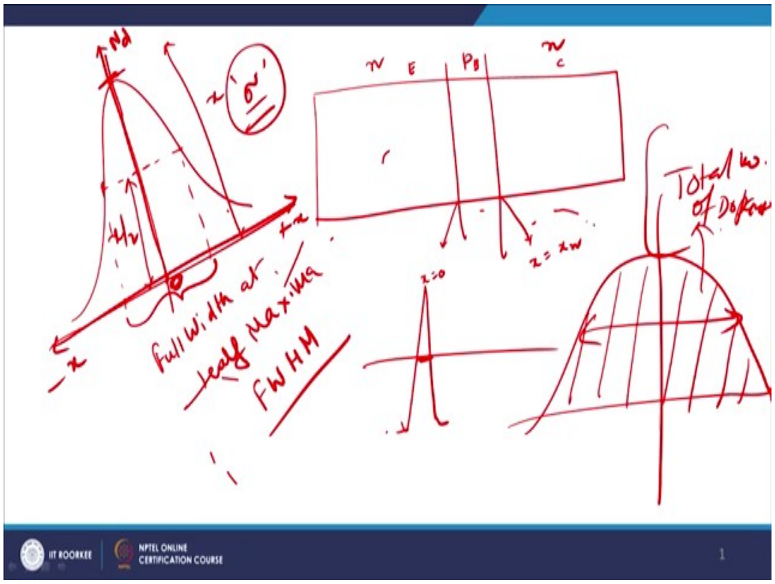

It is known as inverted dumbbell shaped doping profile. The idea here is this is known as this is maximum, right? And this is say, this is X. Then, this is approximately X/2 and we define this width, right? We define this width as full width at half maxima. Right?

So we define full width at half maxima, FWHM right? Now if you make a FW. So this is basically the distance and this is the doping concentration. So this is N_d and this is the X, right? So this is –X , +X , 0. So 0 you have the highest doping and as you move from highest doping to left and right, it falls down. Now if you want to make the doping very very sharp, you just have to make your FWHM very small. Right? You have to make FW... If you want to make the doping a very constant doping, do something like this; spread out. Right? Spread out. And then your FWHM becomes large.

So what is the advantage of a Gaussian profile? The advantage of a Gaussian profile is that it helps you to give a profile or it helps you to control the profile from maybe a constant profile, constant doping profile to a sharp peak profile by simply changing the value of your FWHM or full width of half maxima, also referred to as sigma in most of the cases right? Sigma in most of the cases and that is what you refer to as a standard deviation but technically it is full width of half maxima. And therefore you can see that automatically what you get from here is, that simply by changing the value of FWHM, either you can reach a peak value of doping concentration or you can actually reduce the doping concentration drastically, right? And so and so forth.

So this is what we get. The area under this curve is basically the total number of dopant species total number of dopant species. Dopant or acceptor whatever you want to do, right? So that is the reason, Gaussian profile is most preferred profile in a design because you can control it very, in a much better manner. So due to a graded base region, a built in electric field exists from emitter to collector, thereby adding a drift component to the transport of holes across the base.

This is very very important right? So you see, what I was talking about in the previous case that what is happening is, if you just look at it, that because of the graded base region, there is an electric field from emitter to collector, right? For a PNP, right?

And therefore... so if there is a electric field for example from this direction to this direction. So if you have holes entering the base region, right, there will be that will be always drifted by the strong electric field towards to collector side, right? And that is the reason drift in the base region right?

So that is the reason what we get. So the advantage of it is that you get a larger number of charge carriers on the collector side because of this drift in the base region. Right? We come to the next second order effect and that is basically known as early effect or what is also known as base width modulation effect. We have already studied this but I will just go it a bit fast in this case so that you understand the issues in a much more detailed manner. Base width narrowing effect or early effect is to do with what?

That if you remember, your base is lightly doped as I have written here, this is lightly doped.

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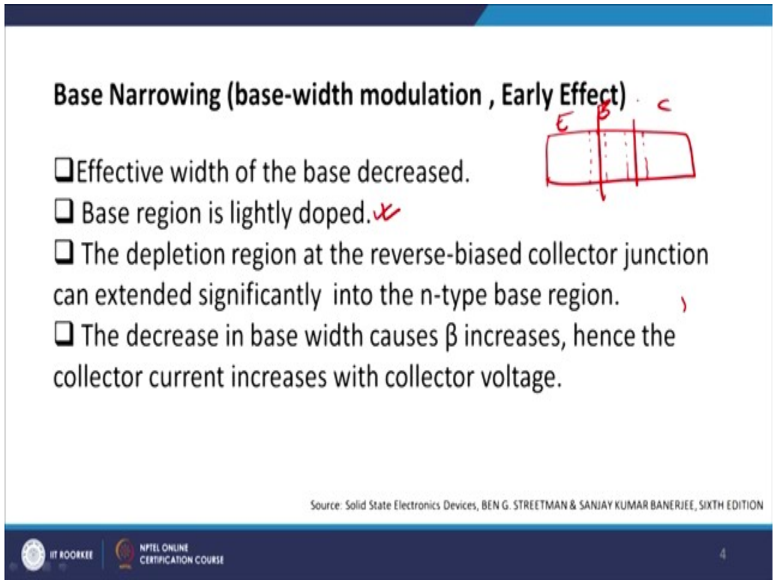

And your, what happens is that if your base is lightly doped, so I have got emitter base and emitter... Sorry this is emitter base and collector. So emitter base junction will have a depletion region like this and collector base will have something like this. But as I have told you previously also that the depletion thickness will be larger towards that region whose doping concentration is low. Right?

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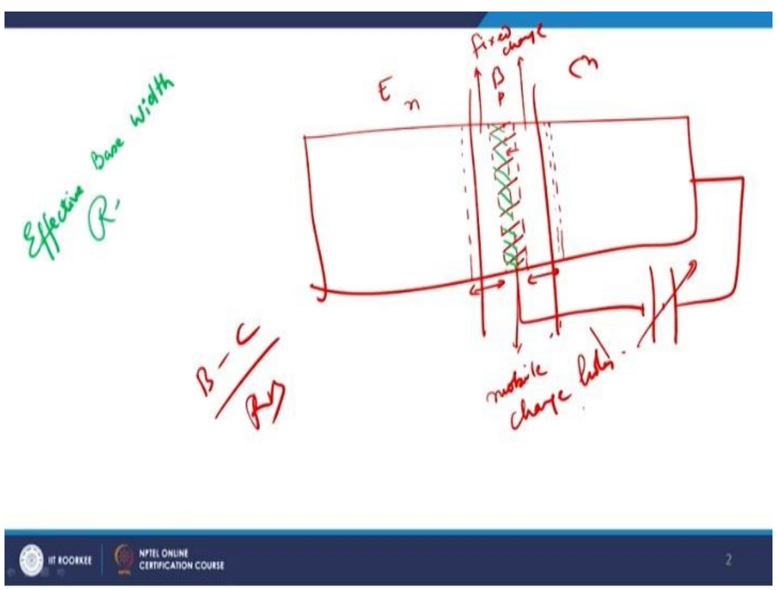

So what I am trying to tell you therefore is that if I have a PN junction or maybe an NPN transistor which is a BJT, and let us suppose this is emitter base collector and since base is relatively lowly doped, I would expect to see the doping concentration something like this. So you will have it like this; they are not equal. Similarly this will have like this and you will have like this. But since emitter base junction will be forward biased, so this total distance will be smaller than this total distance, clear? So what is the effective base width now, is this much.

This is the effective base width where doping is there. Otherwise these are all fixed charge carriers. These are all fixed charge, fix charge. This is the only place where you have a mobile charge mobile charge and those are holes, and those are holes. And these are fixed charge here so basically they don't contribute to the overall current. Now, as I discussed with you when you are active forward mode, your base collector is always reversed biased, right? So when you reverse bias it, that means if this is N P L, let us suppose, if you reverse bias it then this will be something like this, right?

So when you, once you reverse bias it, this depletion thickness will further increase as we had discussed earlier. That means reverse bias will increase the depletion thickness. So the effective depletion thickness increases this side. So what happens to the effective base width? What happens to your effective base width? It reduces actually, if you see very (carefully) clearly. So your effective base width now becomes this much. Fine? It has reduced.

When it has reduced, so this is basically known as therefore, base width reduction or effective base width reduction. So once it reduces, now you have lesser number of carriers in the base region and therefore the electrons moving from emitter to the base side, the recombination will be smaller and larger number of electrons will be reaching to the collector side and you will be reaching a very large value of α, very close to one which is 0.99 maybe. Right?

And if your this base region would have been quite thick, your recombination would have been higher and your collector current would have been much smaller as compared to your emitter current. So with this fundamental understanding, we just now come to the...

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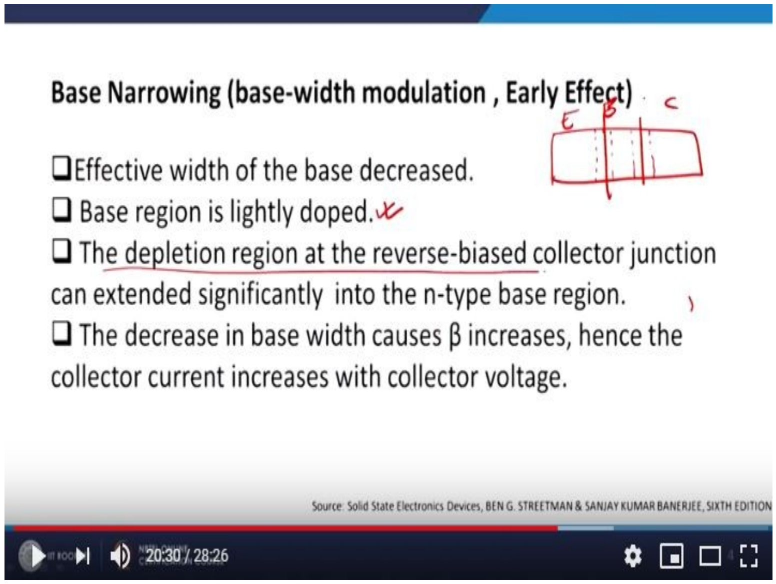

So the depletion thickness at the reverse collector junction can be extended significantly to the n type-base region. We have discussed this point.

And the decrease in the base width causes β to increase and α to increase as well. Hence the collector current increases with collector voltage. Right? So (what do) please understand, till now we were assuming that the collector current is always constant independent of the value of V_{CB}, but now, what we are seeing is since now beyond a particular higher value of V_{CB}, your effective base width is reducing. I would expect to see an increase in the current. So that is what we are seeing also.

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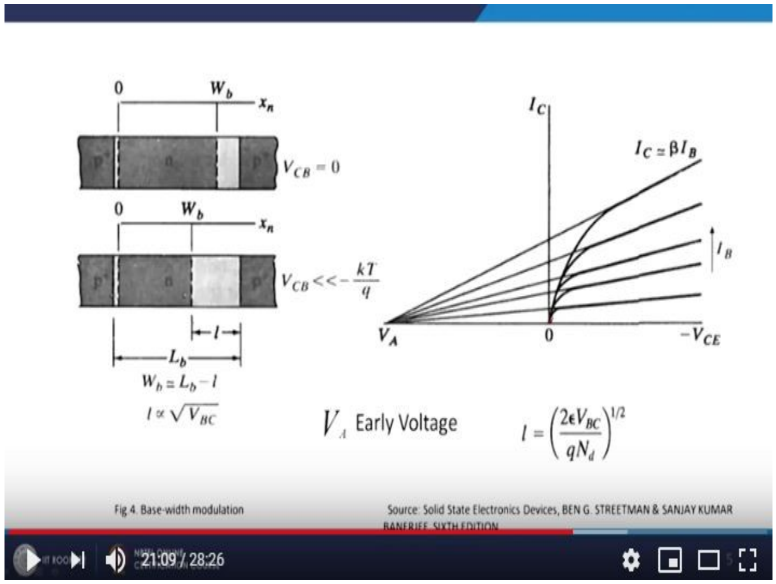

So as you can see here, the current is increasing, it is saturating. There would not have been an early effect, it would not have been something like this, right? It would have been something like this, constant. But then what is happening? At a higher value of V_{CE} or V_{CB}, your this profiling is becoming high, right? Which means that, what is happening is that this value is becoming high and therefore I_C becomes large.

Now the way how to find the voltage if this happens is, that if you back it all of your extrapolate it or interpolate it backwards all the line, interpolate it backwards, the place at where it meets is defined as my early voltage. Right? It is known as early voltage. An early voltage therefore is that voltage at which they will start behaving like a fixed current source, right? And this is what the value of current is.

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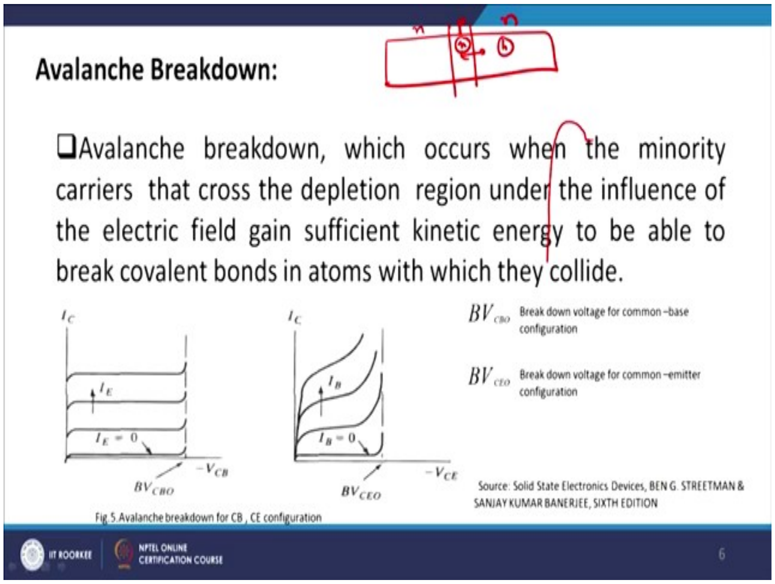

Let me come to the third second order effect and that is the avalanche breakdown. And I think it is very simple and straightforward. Avalanche breakdown is, remember your base collector is always reversed bias, right? We had been talking about for this long time that base collector will always be reversed bias. So when the base collector is reversed bias, for, so you will have minority current carriers (hole) holes here. And you will have electrons as a minority current carriers here, right?

Now when you reverse bias it, electron from N-type and holes from P-type won't be able to move because the depletion thickness is very large. But for the minority current carriers which is hole on the N side and electrons on the P side, it is more of a hill. It is going down. It is not a up hill, it is down hill, right? So therefore I will expect to see a large amount of current because of minority current carrier. But since the number of charge carrier, minority current carriers are very low, therefore the charge associated with it or the current associated will be very very small.

Yes, it will be small of course but let us see what happens.

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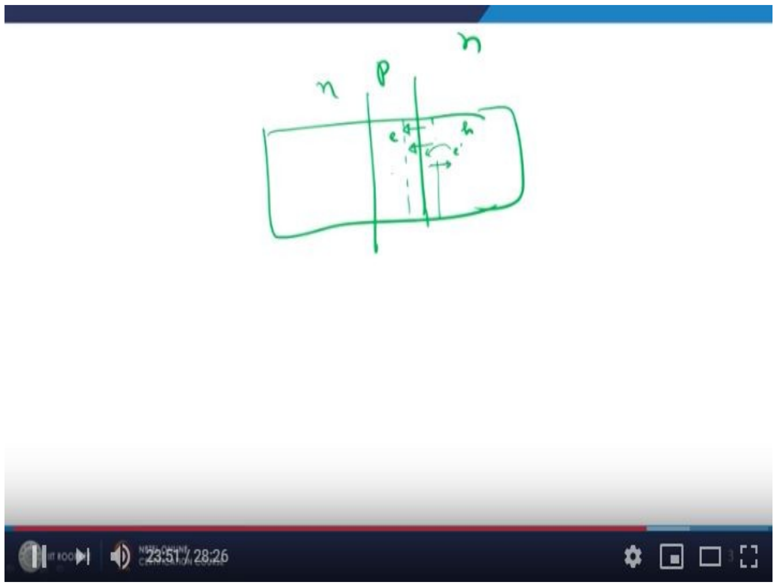

Now this…Once they start moving, so I have this junction, this is emitter based junction and I have got NPN and electrons are available here and holes are available here, right? So the electric field internally which is there in the depletion region between P and N because it is reversed bias so I have a depletion region here, right? (And I would expect) so the internal electric field will be from this side to this side.

So any hole, any electron trying to enter from this side to this side, electron is a majority current carrier in N type, will be forced to go this side. Similarly any hole entering from this side to this side will be again forced to go this side. So any majority current carrier contribution will be almost 0. Anything which will be coming will be directly coming from emitter.

But for these holes and electrons which are minority current carriers in collector and base respectively, if the hole enters here it will be dragged by this electric field within the depletion region to reach this point. So if you go on increasing the value of your reverse bias collector junction, right? If you go on increasing it drastically, so these electrons and holes will gain large amount of energy and when they pass through this depletion region, they will ionize and form electron and hole pairs.

So what will happen is, beyond a particular point, you might have a suddenly large increase in the value of electron, right? And that is what is known as an avalanche breakdown.

But due to this sudden electron charge, you will have a large electron current and therefore if you plot I_C versus V_{CB}, it is this constant we have discussed this point, constant current. But as you go on making it more and more negative biased and make it larger, suddenly a time comes when the current suddenly increases, almost drastically like this.

And the reason is that you now have large amount of ionization and large amount of electron-hole pair formation because of which there is a large current available to you, right? These are primarily, electron-hole pair formation is taking place. You can also have another thing that electrons become move very fast and they ionize the atom. So the exterior most electron from the (kinetic is so) the kinetic energy of the incident electron is so large that it directs all its energy to this peripheral atom, electron and the electron comes out of the atom, right? And it becomes a free electron.

In any case you will have a very large quantity of free electrons which will be available and therefore you could expect to see a sudden increase in the current, right? This breakdown voltage is defined as V_{CBO} when it is a common base configuration. Also referred as B_{CEO}, BV suffix CEO when it is a common emitter configuration, which is there, right?

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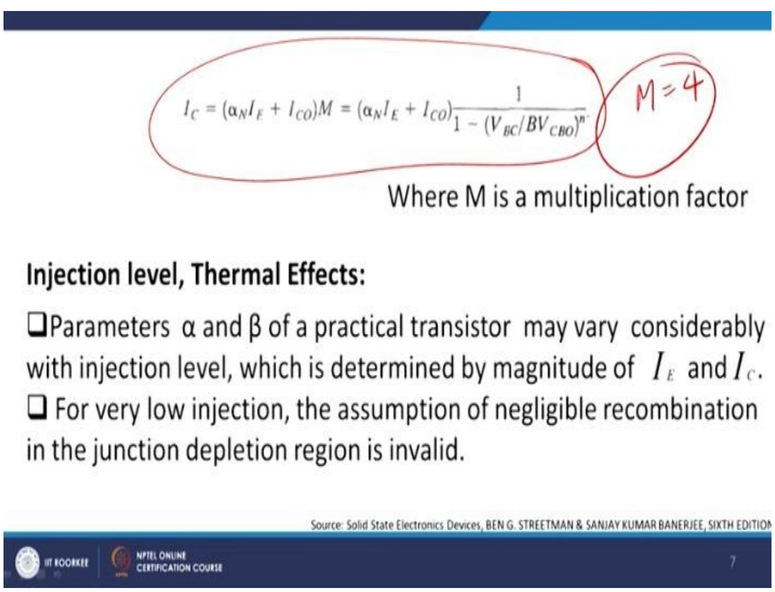

So we have these two types of configurations available. This is the net current which one sees because of the multiplication factor, because of M.

M is the multiplication factor primarily meanings that for each inonization how many number of electrons are formed. So if one electron comes and form four electrons in the multiplication factor M is equals to 4, right? And you will have four number times of electrons and hole current available right?

So with this, we have understood the basic three mechanisms, basic three mechanisms of breakdown. When we meet next time, we will be actually looking in to the next two mechanisms a second order effects. As you can see therefore, these are special cases as I discussed with you. Why special? Because only and only when, when your collector base or a base collector junction becomes larger than this breakdown voltage, then only you will expect to see a very large increase in the current.

Otherwise the current will be almost constant or remain as it is. So therefore these effects are known as second order effects. What we have learnt? Avalanche breakdown we have learnt, one. We have also learnt your drift of charge carriers within the base region a second order effects and we have also learnt about the early effect or effective base width modulation.

When we meet next time, we will be actually looking into the other facts, as far as this dimension goes and we will see what are the other facts. We will look in thermal effects and we will be looking into the base resistor or emitter crowding effect. So these two effects we will look and that will ensure that we will be finishing off BJT with the understanding of these few fundamental things. Thank you very much.