Semiconductor Devices and Circuits
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Lecture - 30
BJT : IV Characteristics

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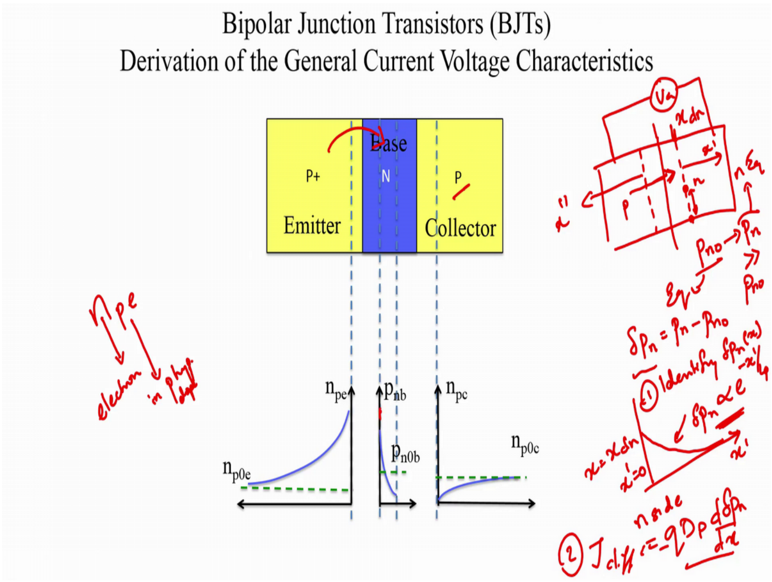

So, now let us get into the Derivation of the Current Voltage Characteristics for a BJT and the starting point for that for this current voltage characteristics is going to be something that you are already familiar with, which is in the case of your pn junctions what was our strategy to derive the current voltage characteristic. So, we had your P side and you had your N side and you had a depletion region ok, you had a depletion region, what was the strategy for the current voltage characteristics. We saw that when we forward biased this diode or when we apply any voltage Va whether its forward or reverse bias. We had holes diffusing through ok. So, let us say forward bias we had holes diffusing through and you had this excess minority carriers coming in to the N side right.

So, we had an equilibrium population of holes on the N side, which is the number of holes on the N side and that stands for the equilibrium value that was (Refer Time: 01:26) notation and by applying a forward bias this became pn ok, which was greater than the equilibrium population and the excess injected carriers was delta pn which was basically your pn minus Pno. So, that is equilibrium that is non equilibrium and this is the excess due to the non equilibrium and we said that we will first identify delta pn as a function of x.

So, we said that on the N side we are going to have this coordinate system which was x dash which had a starting point at x dash equal to 0 which corresponding to x equal to xdn that was x equal to xdn and we have solved the continuity equation and we first found that this delta pn varied exponentially with distance ok, to sort of proportional to e to the power minus x dash by lp ok.

And then after identifying this gray gradient we then said we will now derive the current voltage characteristics by using that because the current is now diffusion current we said that the current was due to the p was q minus q Dp d delta P on the N side by dx and that was the current density. We are going to do the same thing here the only problem is that we have two junctions and we have to solve for both the junctions so; we need to have three sets of coordinate systems ok. So, we had if you remember the pn junction for the N side we had this coordinate system x dash and for the P side we had another coordinate system which pointed in that direction and it made things easy and it is we are going to do the same thing here ok.

Now, we are going to watch the minority carriers in each segment and the emitter. What are the minority carriers? Minority carriers are the electrons in the emitter which is p doped ok. So, the symbols here let me just spend a minute addressing the symbols when we say npe it implies that we are talking about electrons in the P type in a P doped semiconductor which means it is the minority carriers and this e stands for the emitter and when we say if we say Ppe we are talking about the holes in the P types doped emitter ok, which is the majority carriers.

And when we say np 0 e it is the equilibrium concentration of this whereas, the npe is what happens when you apply a bias which is the non equilibrium concentration. So, npoe is basically the equilibrium concentration it is npo in the emitter. So, thatis thatis that is the symbol here and if this e is replaced by C we are talking about the collector and if its replace by b its talk we are talking about the base ok. So, that is the notation used it is quite intuitive if there are any difficulties do feel free to send me a message.

So, what we are plotting here is the minority carrier concentration which is the electron so, the Emitter is P times the minority carriers electrons. So, electrons in the p type emitter and these are the electrons that have been injected from the base into the emitter because of the forward bias action of the diode and they have got a variation that looks like this ok, and in the base the minority carriers are the holes, that have been injected from the emitter into the base due to the forward bias action and they have got a concentration that looks like that looks like this because of the recombination also little recombination in the base and that is P N in the base ok. And in the collector the minority carriers are again the electrons and the collectors reverse biased and therefore, you have an electron concentration that varies like this.

So, you have N in the p type collector and you have a electron concentration that varies like this remember the base collector junction is a reverse biased. So, that is why you see the concentration variation in the manner shown and this junction is forward biased ok.

So, that is why the concentrations are as shown because if you recollect we will again be making use of this idea the concentration at this interface, which we use as a boundary condition is basically the equilibrium concentration into e to the power q times the voltage applied across this junction ok, in this case is the base emitter voltage I am sorry it is the emitter base voltage because that is the pn by kt minus 1 and by just understanding the nature whether this is positive and negative you can identify what the concentration profile is ok. You can understand the point the starting point of the concentration profile all right. So, that is the profile.

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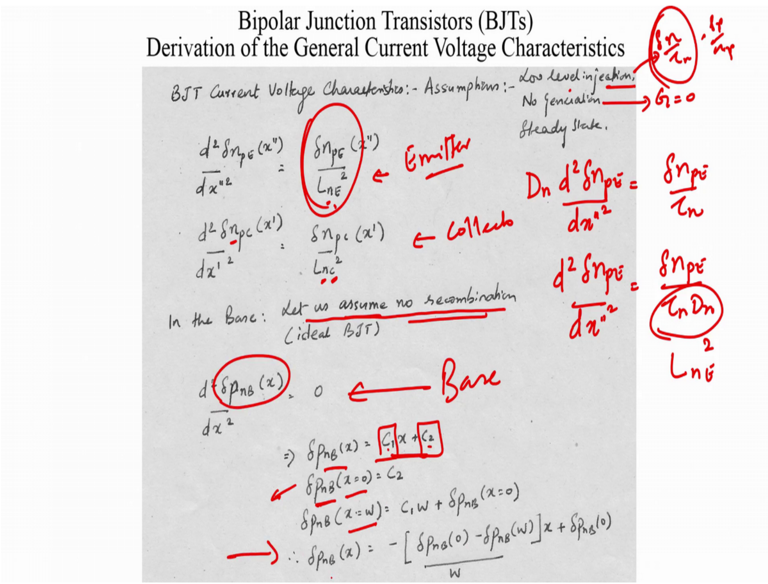

Now, all we have to do is sit down and solve the continuity equation in the collector the base and the emitter and you will have your current voltage characteristics ok. Now before we do that one thing which I have not marked out here is the coordinate system. So, you can see three different coordinate systems. So, this coordinate system I will just call it as x which means x equal to 0 is at the is defined at this depletion boundary ok, the base the depletion boundary due to the base emitter junction and the depletion boundary which is sitting in the base very specific ok.

So, that is my x equal to 0 point and if I am correct the this coordinate system is defined as x dash I would like to call x dash equal to 0 as this point here and this coordinate system is x double dash with x double dash pointing in the opposite direction and with x double dash equal to 0 define at this interface and the reason we do it is simply makes the mathematics a lot more easier because you can independently treat these three differential equations without worrying about any translation of the variable etcetera ok, just makes it just simplifies the mathematics a lot more and we can use the well established solutions again and again ok.

Because we are going to treat these three independently and just bring in the effective idea or the impact of these three solutions at the last step. So, we have these three coordinate systems and we have concentration profiles of the minority carriers and we are going to identify. So, here I have just qualitatively sketch the profile, but you want the exact mathematical variation of the profile you want to be solving the continuity equation for these three regions ok. Now the continuity equation for these three regions are written using several assumptions the first is low level injection. So, that I can very conveniently use my recombination rate, which is basically my delta npE or whatever delta np by tau N, so, I can use the recombination rate of that kind.

Then there is no generation; that means, we are not thrown light on the BJT ok, there is no new generation of no photo generation. So, let me just say no photo generation of carriers, let me very specific and we are talking only about steady states. So, we are not talking about transients so, the continuity equation will not have a time component here ok. So, we are in steady state low level injection condition and here in the continuity equation if you and I want to understand what this means it means this G is 0 the G is 0 this means I can use my very convenient delta N by tau N or delta p by tau p recombination rate and what this means is that any derivatives with time is 0 ok. So, these are the three conditions and we will throw it into the continuity equation.

And of course, electric field component are not important. So, that is another aspect so, the continuity equation is something that you are already familiar with ok, we have used this for the pn junction diodes. So, I am not going to elaborate a lot on this I made one leap right away which is I have represented this term here as the diffusion length of the electron. So, where did this Ln square come from the actual continuity equation is it is going to be Dn d square delta N p in the emitter by dx double dash square is equal to delta npE by tau N and therefore, this becomes d square delta npE by d double x square is equal to d delta N delta npE by tau N D N which is nothing, but your Ln in the emitter squared ok. So, that is that is the leap we have taken here.

And similarly for the collector so, that is for the emitter right. So, that is the continuity equation in the emitter and in the collector we have another continuity equation because they are the minority carriers are n. So, d square delta N pc by dx dash square because that is a new coordinate system in the collector is equal to delta N pc as a function of x dash by Ln c square ok. So, this is the emitter and collector and N stands for the diffusion length of the electrons.

So, these are things that are already familiar with, but for the base there definitely is recombination, but for now we will just assume that there is absolutely no recombination the BJT is working in a manner that we dream of, which is the base width is so narrow that there is no recombination that is that never really happens ok, but it is a big assumption, but nevertheless an assumption that will simplify lot of things for us and which will give us a very intuitive glance as to the working of the BJT. So, let us at this point assume that there is no recombination in the base, which means that this term see this term comes appears because of the recombination so, that is a recombination rate right.

So, what this is saying is that there is no recombination, which mean that term is 0. So, this is the differential equation in the base. Now this is very easily solved right so, the solution to that is simply it is got a linear dependence it asked for a linear dependence in of the minority carriers with respect to x and the way you find out these two constants is that you identify what is the minority carrier concentrate, which is the holes in the base at x equal to 0 and at x equal to w. So, what is a x equal to 0 and x equal to w we are asking for what is the concentration here and what is the concentration here and if you know these two points you identify these two coefficients and therefore, this is the general solution for delta P n in the base ok.

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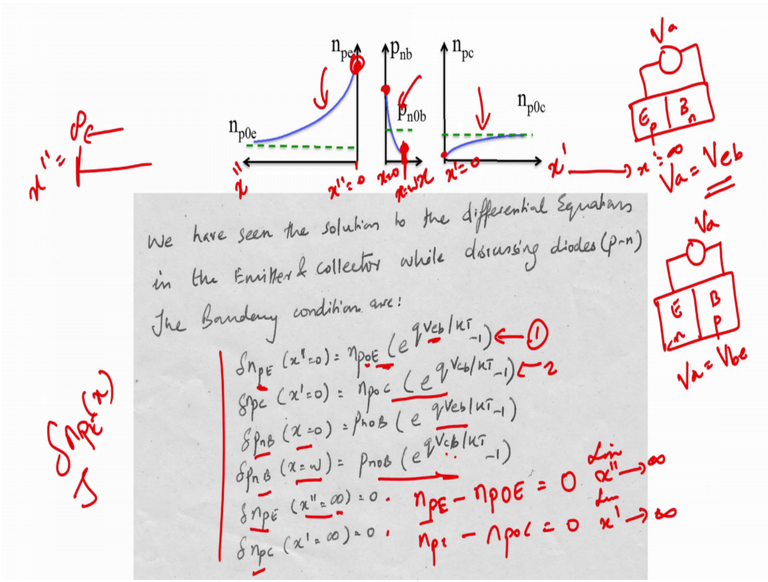

Now, what are the boundary conditions? We have listed three different differential equations and I am sure all of you know how to solve these it is quite obvious as to what the solutions are this will have a form of whatever your x double dash by LnE plus B e to the power minus x double dash by LnE and similarly for this one with different a and b ok. We already we have already seen these solutions in the in the case of a pn junction we will do that again, but what are the boundary conditions? The boundary conditions are exactly what we used for a pn junction. So, if you have understood pn junction theory well BJT is quite straight forward because we are just using the same ideas again and again.

So, what are the boundary conditions? So, what we are looking at is np in the emitter at x double dash equal to 0 so, that is my x double dash that is x and that is x dash at this point. So, we are looking at this and that value is given by boundary condition 1 ok, and we have already seen we have already applied this boundary condition at the in the pn junction diode npoE is the equilibrium concentration it e to the power q Veb by kt minus 1. Veb is the if you think of the base emitter junction that is the base emitter junction we are looking at a pnp BJT. So, that is my base emitter junction and this is the applied voltage ok. So, Va is the same as your Veb in this case, but on the other hand if it was a npn junction if that was the npn base emitter junction then that would be the way we had defined the applied voltage in the pn junction theory and therefore, my Va would be equal to Vb ok. So, since we are talking about pnp junctions you have Veb.

So, delta npE at x double dash equal to 0. So, that is x star double dash equal to 0 is given by this term ok, the same boundary condition we used in the pn junction diode delta npC at x dash equal to 0 that is basically this population here is equal to this that is your second boundary condition ok, that is my x dash equal to 0 point delta Pnb at x equal to 0 that is basically this is given by this delta Pnb at x equal to w ok.

So, that is that is my let us say x equal to w and what is the population here that is given by the collector base junction because that that boundary is now at the collector base junction interface it is at this interface and therefore, that is my x equal to w and since that junction is reverse biased you see that you know this value takes this particular nature.

Finally, what are the values very far off at x double dash equal to infinite ok. So, that is x double dash equal to infinite asymptotically and that is x dash equal to infinite. So, what are the values there in the case of delta npe x double dash equal to infinite is 0 and delta npc at x double dash equal to 0. So, what this means is that if you look at nPE minus the equilibrium concentration nPOE there is not much difference and; that means, nPE approaches the equilibrium concentration as we head towards infinite and npC also approaches the equilibrium concentration as we head towards infinite.

So, the in the limit of x double dash heading to infinite and in the limit of x x dash heading to infinite nPE minus nPOE is 0 and npC minus npoC is 0. So, that is what these two boundary conditions mean. So, you apply so, you have three equations you have three second you have three equations and therefore, you have six unknowns ok, you will have A B let us say let us call it as A of the emitter, B for the emitter then A for the collector, B for the collector and you have your C 1 and C 2 as I have shown you here you have six unknowns and therefore, you have six boundary conditions with which you can identify every unknown and therefore, you have the exact solution for the nature of the minority carrier variation with distance ok.

So, what we are going to do now is simply solve the differential equations apply the boundary conditions get the variations of delta np as a function of x etcetera and then find the current the diffusion current ok, just like we did in the pn junction.

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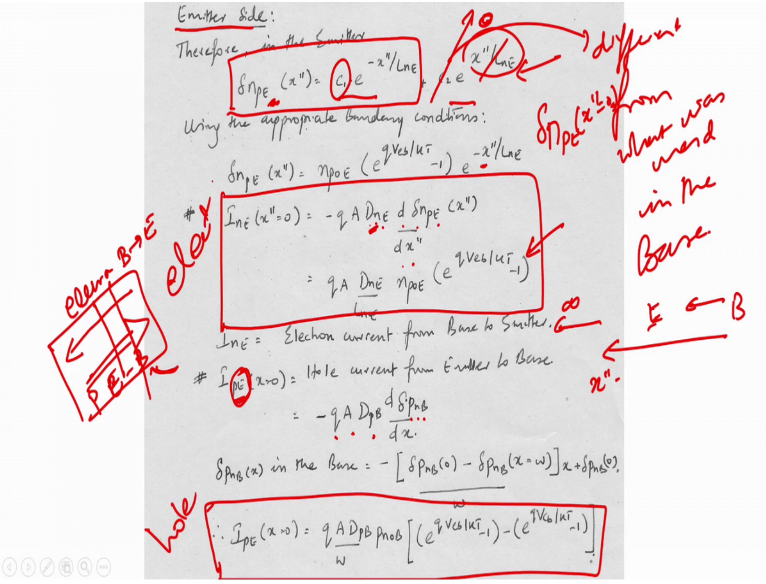

So, first let us do the emitter side ok, it is all the same I mean the methodology is the same. So, that is going to be the general solution I have used the same C 1 and C 2 please do not mistake this for the same coefficients as used in the base in the case of the base. So, we have used the same variable C 1 and C 2, but there is just a matter of habit. So, if you if you would like you can call it C 1 e and C 2 e, but this C 1 and C 2 is different from the coefficients we used for the base ok. So, please note that ok. It is different from what was used in the base ok. It is just a matter of habit you to which I have used C 1 and C 2 again.

So, you have delta nPE is going to have this particular form ok, you have an exponential of a minus x double dash by LnE and plus x double dash by LnE. So, we use all the boundary conditions you will find that at x double dash tending to infinite, what happens as x double dash tends to infinite this carrier concentration goes to 0 where it as x double dash tends to infinity this term blows up therefore, we cannot allow C 2. So, C 2 has to be 0 and therefore, this is the only solution and we identify C 1 by using the condition of delta nPE at x double dash equal to 0 ok, which was this boundary condition here and that you can identify your concentration gradient the excess electron concentration in the p doped emitter to vary as this with the x double dash coordinate system pointing in that direction it goes from the base to the emitter and all the way till infinity.

So, that is my concentration gradient of N in the p type emitter. So, what is the current? The current is the diffusion current so, here we have written the total current and now the current density therefore, we bring in the area of cross section. So, you have the q Dn E which is the diffusion coefficient of the electrons in the emitter into d delta nPE by dx double dash and multiplied by the area of cross section to give you the total current and just like in the case of pn junction diodes the way we want to extract the current is by looking at the current at the depletion boundaries we want to measure the diffusion current here you see the diffusion current is going to vary with space, but if I were to measure the diffusion current here I must also account for the other current mechanisms right.

So, I would rather prefer to get the diffusion current right at this interface and therefore, we calculate the diffusion current at x double dash equal to 0 and we find that that is the diffusion current of electrons in the emitter. What about the holes from the emitter? The holes from the emitter are moving to the base so, you have what we have now calculated is the electrons pushed by the base electrons going in from the base to the emitter, what about the larger contribution of the holes coming in from the base to from the emitter to the base. So, for that we need to solve the differential equation of the minority carriers in the base which is my IPE at the emitter the whole contribution of the emitter current this is the electron contribution of the emitter current ok.

The whole contribution of the emitter current located at x equal to 0. So, we are going to measure that at x equal to 0 we are going to do that calculation here. So, we have already calculated for this is done you are now going to calculate for this. So, that is nothing, but q into A into D p B into d delta n p in the N type base by dx and we have already found that since there is no recombination in the base we found that our delta npB had this particular form. So, if you remember if you recollect when we solve the differential equation for the base we said there is no recombination and therefore, that was the solution. So we are going to use that solution now ok, there is a by W there which probably is not visible on the screen ok.

So, we are going to use that solution now and we find that the current due to the holes from in from the emitter is given by this particular expression ok. So, that is the current that is the electrons moving in from the that is the electrons from the base to the emitter you have a forward bias base emitter junction, that is the electrons from the base to the emitter this is the holes from the emitter to the base and the total current is therefore, the sum of these two ok.

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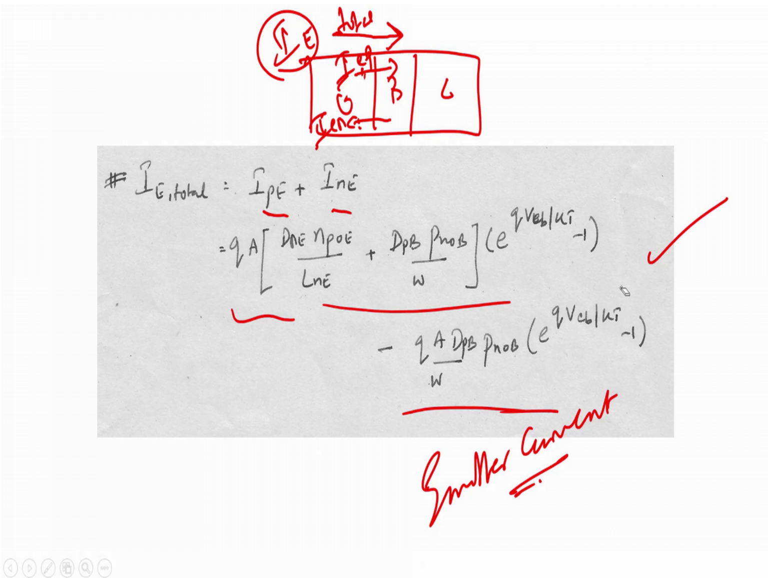

So, we are now talking about the emitter base collector we are talking about this total current. What is IE? It is got two components it is got the electron current from the base to the emitter and it is got the hole current from the emitter to the base and the sum of these two is the total IE, which is given by the sum of IPE plus INE it is basically summing these two expression is that we derived. So, this is the total current from the emitter so, that is the emitter current.

So, we have not. So, remember this is being done in any mode right we have not said that Veb is forward biased was greater than 0 or Vcb is less than 0 this is true for saturation cut off active it does not matter we will later on adapt the values for this and see which terms dominate. So, this is a very general derivation.

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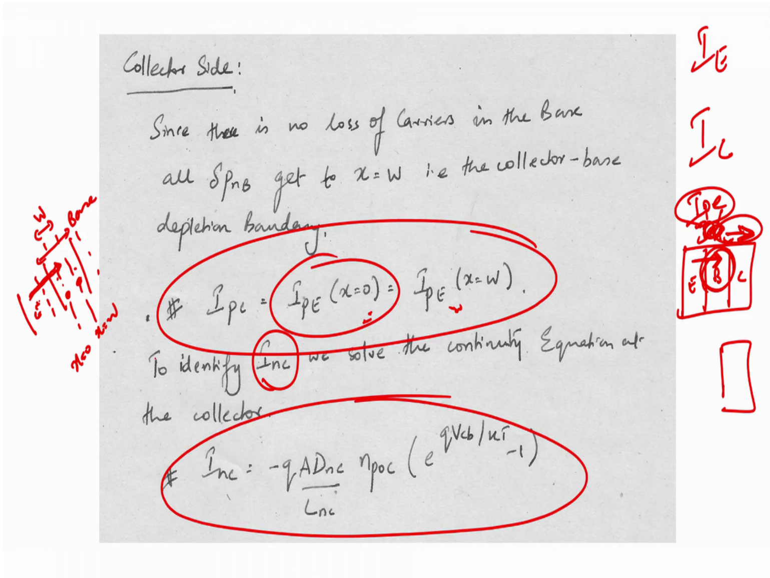

So, now let us do it on the collector side. So, we know what IE is what is the collector current? The collector current ok, now how do we go about the collector current. So, collectors the collector base junction is a reverse biased right. So, this is the argument we make.

We say that there are no loss of carriers in the base ok. So, we have the emitter base collector we know what IpE is ok. So, we say that there is this IpE came into the base and as per our assumption there was no recombination in the base therefore, there is no loss of Iep therefore, I am sorry IpE is that I do not know whether what I mean is the whole current from the emitter so, IpE ok. So, that current is the entire entering the collector without any loss of current because the base is not doing any recombination. So, there is no loss of carriers and therefore, the all of IpE is going to go into the collector.

So, IpC that is the holes entering the collector is simply equal to IpE at x equal to 0, which is equal to IpE is at x equal to w ok. So, what this means is just you reiterate so, you had your x equal to 0 boundary that is my x equal to 0 that is my x equal to w that is the base width ok, this is the base and you have your depletion boundaries here this junction is forward biased that is the emitter base junction is forward biased. So, you have a lot of holes that came in and we calculated the hole current here at x equal to 0, what we are saying is that we had assumed that the base did not recombine any of these holes therefore, the whole current here is equal to the whole current here is equal to the whole current here ok.

So, IpC is nothing but IpE at x equal to 0 which is equal to IpE at x equal to w if there was recombination then this greater this is not equal to this and you cannot make this argument ok, because these holes would not have entered the base collector junction. Now to identify the electron contribution in the collector what do we do we solve the continuity equation at the collector and we go through the same exercise which is which is to try and identify the solution for the differential equation.

So, all this differential equation for the collector and apply these boundary conditions this one here and this one here you apply those two boundary conditions and you will go through the same process like what we did for the case of the emitter and we will find that the current in the electron current in the collector is given by that the hole current in the collector is given by this term that we have already calculated and therefore.

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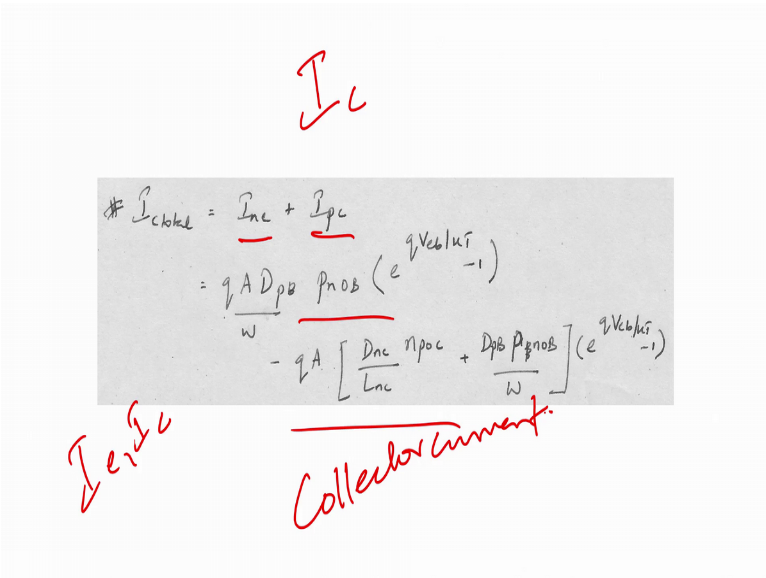

The total current in the collector is InE plus IpC which is given by this term. So, that is my collector current. So, IC that is my collector current. So, you have now calculated IeEand IC.

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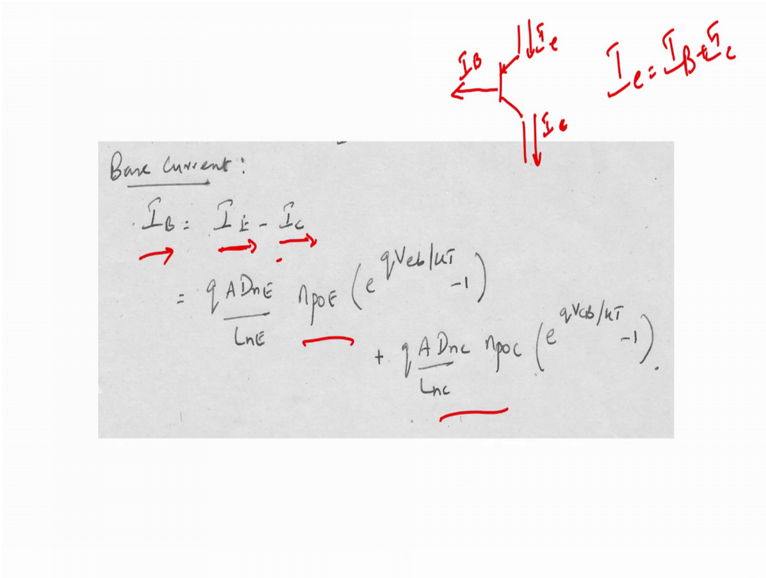

So, finally the base current. What is the base current? We will simply use Kirchhoff's law we will say that there was a current through emit from the emitter there is some current with the collector remain current remaining current is the base current. So, if in case of the pnp there was IE there is some IB and there is some IC ok. So, in other words IE is equal to your IB plus IC. So, therefore, IB is simply the difference of the emitter and the collector currents and that is simply given by this term here. So, that is the general derivation of the emitter collector and base currents using the continuity equation and looking at the minority carrier distribution profile in the three in the emitter base and collector and then solving for the diffusion current in the three region. So, this is the general current voltage characteristics.

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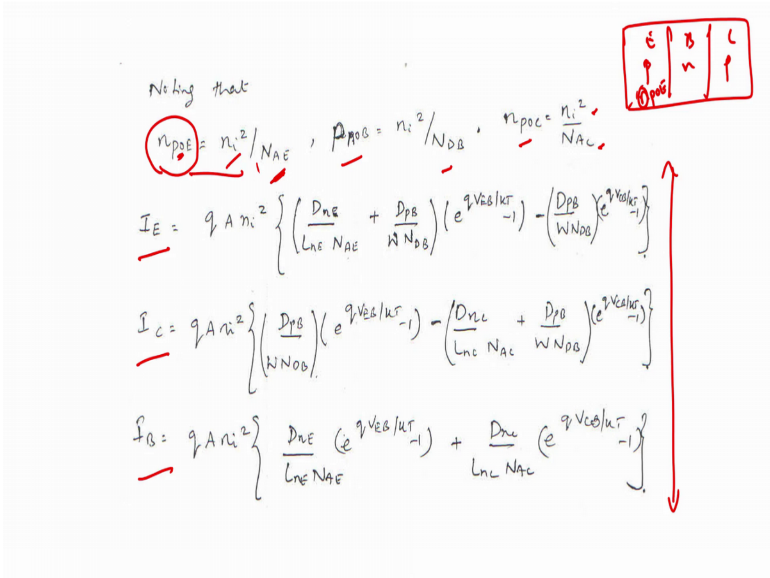

So, just to put them all together I have written down the emitter current, the collector current in the base current and I have taken I have gone one step further, which is since we know the this is the equilibrium concentration. So, it is got these a nPoE is the equilibrium concentration of electrons in the p typed emitter right. So, we have my we have the pnp emitter base collector npoE is the number of electrons at equilibrium which is ni square by the doping etcetera like doping concentration of the emitter. So, this is quite large so, therefore, npoE is expected to be quite small.

Similarly, PnoB is ni square by NDB, PnoC is equal to ni square by N AC and therefore, we just substitute that and we get expressions of this kind here ok. So, it is just it is just substituting that and sort of summarizing the collector emitter and base currents.

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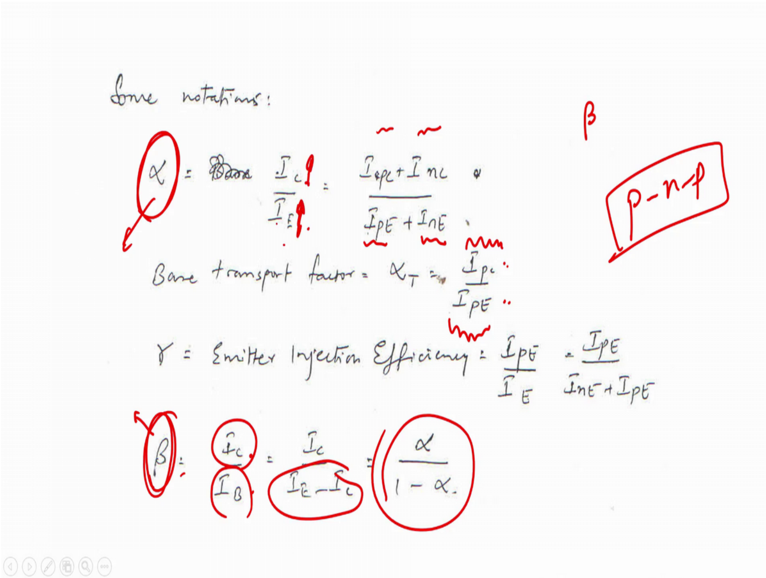

Now, we have some other notations that many of you would be familiar with ok. So, we can define several terms there is the beta factor for a BJT. So, when you have a BJT particularly if your interest in building circuits or forming circuit analysis there is a beta factor, which is basically your IC by IB and then there is an alpha factor which is IC by IE.

Now, what is IC? IC it is got the whole contribution and the electron contribution IE is got the whole contribution and electron contribution, there is something called as a base transport factor which only looks at the hole concentrations ok, what is the what is the whole population that the collector collected divided by the total whole population the emitter emitted ok, it does not take into account the entire IC in IE, but it is a base transport factor you know how efficient was the base and transporting the holes in the case of a pnp junction in the case of an npn we will be interested in the electron population and here you have gamma which is the emitter injection efficiency you know how efficient is the emitter in injecting holes in the case of a pnp.

So, all this is for the pnp junction that we analyzed so, the emitter. So, what is the so, you want to push a lot of holes and you know not have too many electrons come in from the base and all those depends upon the doping of the emitter.

So, you have all these terminologies most of you might be familiar with beta and alpha, but since you have already derive the general IV characteristics these are now you know just terms that you could use for doing circuit design, if you prefer ok. So, you now know what is what is hidden behind these terms and since IC IE and IB are also related by this relation beta and alpha are also related. So, generally if you want a good active mode operation you would like the BJT to have small IB large IC and therefore, very large value for beta and a close to one value for alpha, which is all the electrons from the emit all the holes from the emitter where collected by the collector with very little recombination in the base. So, you that is what you would like.