Semiconductor Device Modelling and Simulation

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Lecture – 22
Bipolar junction Transistor (Contd.,)

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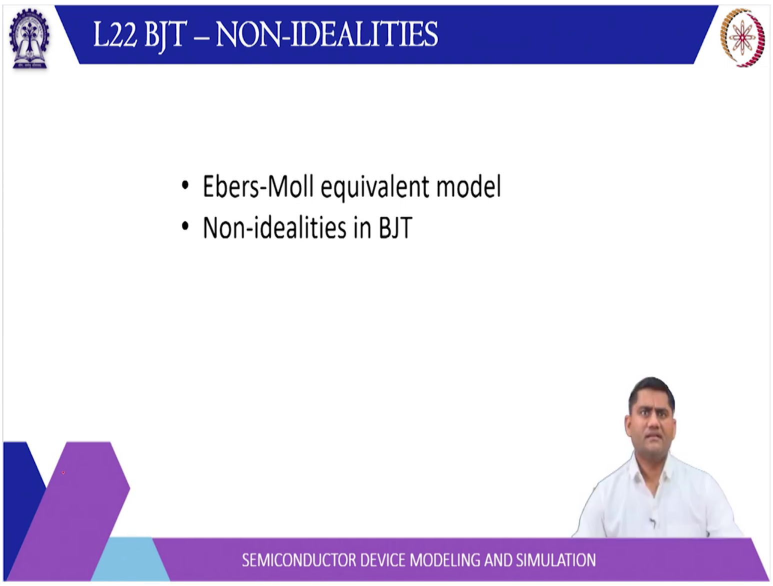

Hello, welcome to lecture number 22 we have derived the current equations for the BJT now we will consider Ebers-Moll equivalent model then non-idealities in BJT.

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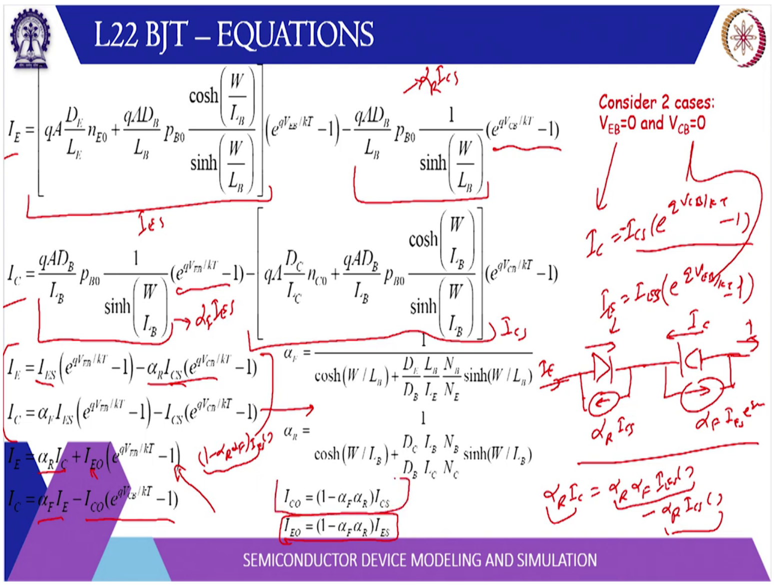

So, this basically slide summarizes the equations that we have derived. So, you can see here this is I E n, I C n they are very similar then you have I E P and I C P, I E Ps obtained from the derivative of Delta P B at x equal to 0, I C P is obtained from the derivative of Delta P V at x equal to w. And you can also notice one more thing here the coefficient for exponential q V C B by kT in I E P is same as the coefficient for exponential q V B by kT in I C P and vice versa that is because from the base both side appear symmetric.

So, there are two Junctions basically emitter base Junction and base collector Junction. The difference arises because of the different difference in the doping of emitter and collector. So, because of this difference in the doping the factor here will slightly change. So, because of the difference in the doping this I E n and I C n will be different. As far as I E P and I C P is concerned the slope will be different at the two ends if you are injecting carriers from the emitter then by the time they reach to the base Junction some of them would have recombined.

So, the current will be less if you are considering the injection from The Collector by the time they reach to the emitter some of them would have recombined. So, that is the reason that there is some difference there otherwise according to equation it is symmetrical so, for example if you consider x like this. So, if you define x from this end and then this is w then you will have equation where coefficient for V E B and V C B will be interchanged basically.

Then of course these are the expression for the emitter injection efficiency base transport Factor common base current gain and common emitter current again and when you add these two I E n and I E P you will get the I E current, so, this expression for I E this expression for I C. Now these equations actually look very big equations. So, one may be you know tend to think that you know how will I remember or understand this equation.

So, what people have done these equations are written in some form where this whole thing this is written as I E S that is basically emitter saturation current and this term in the bracket is written as I C S that is a collector saturation current. So, if you leave the emitter open. So, there is a V B 0. So, this term will go to 0. So, your IC is basically I C S times. So, for V E B equal to 0 your I C S equal to I C S exponential q V C B by kT minus one.

Similarly for V C B equal to 0 this term will go to 0. So, your I E is equal to I E S exponential q V E B by kT minus one. So, when either of the junctions voltage is 0 it basically acts like a diode and these are the normal diode equations with their respective saturation current then you have this other terms which are dependent on the voltage across other Junction. So, this is for I C S, I C S exponential q V C By kT then plus some term.

Similarly for I E there is I E S exponential q V B y kT minus sum term. So, let us call this as Alpha times ICS and let us let us call this as Alpha times I E S. Now this is basically coming to emitter. So, this call is Alpha reverse and that is call this as Alpha forward. So, there are two diodes here you can understand like this. So, this is IES exponential q V B by kT minus one this is ICS exponential q V C By kT minus one.

So, these are two terms then this other term. So, you note the direction this is I E. So, I consists of this term then minus. So, minus means its direction should be opposite. So, this is Alpha R times I C S whatever I see I see this term is negative. So, this is minus I C S exponential q V C By kT minus one then plus this Alpha. So, plus B is a current Source in this direction and we call it Alpha F times I E S exponential q V B by kT minus one and the collector direction of collector current is like this.

So, this is positive and the diode current is minus negative sign. So, these two equations are written here it is pictorially represented here. Now this model was given by two scientists one is called James Eber and Johan Mall it was introduced in 1954 and it is popularly known as ever small model now we can do some further rearrangement here and we can say that I E we can represent this I in terms of I say instead of these two diode currents IES and I C S. So, what we can do let us multiply this IC this equation by Alpha R.

So, what we have here Alpha R times I C is equal to Alpha R times Alpha f times I E S exponential term minus Alpha R times ICS exponential term now Alpha R I C S exponential term appears in I E. So, I E can be written as Alpha I C minus alpha alpha F times I E S with exponential term and plus this I E S exponential term. So, is appearing here as well as here. So, so this is done Alpha R I C Plus Alpha R Alpha f 1 minus Alpha R Alpha up right.

So, this is basically 1 minus Alpha R times Alpha F times I E S some exponential term. So, this is basically I E O. So, I E O is one minus Alpha R Alpha F times I E S. Now why we write in this form because we are writing I E in terms of alpha I C, so, this is Alpha R then I E O is basically if I C is 0. So, this is the emitter current when I C is 0. Similarly for I C we can write Alpha F times IE minus I C O exponential q V C B by kT minus one and then I C O is by similar logic its one minus Alpha R Alpha F times I C S.

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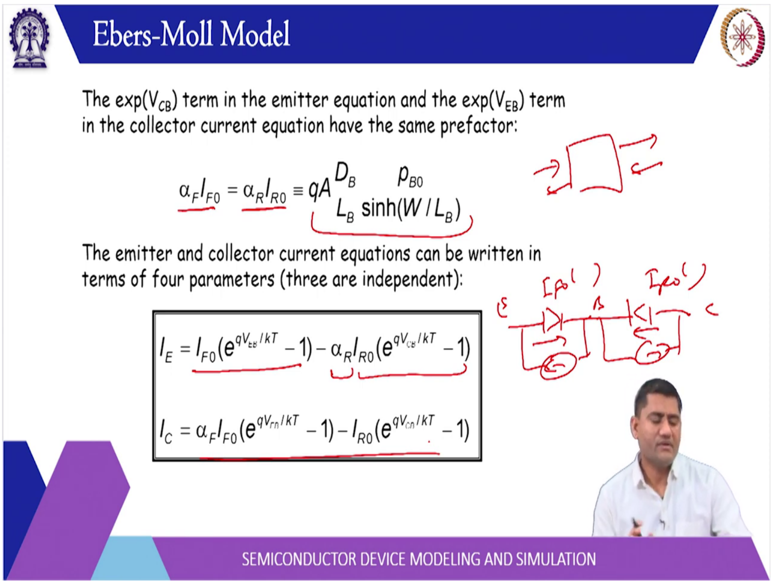

Now another thing you can notice here Alpha F times I F naught is same as Alpha R times I R naught that you can easily see here these two terms the I E due to I C S and this term I C due to is they are same basically the coefficients are same q A D B by L B one over sin hyperbolic. So, this basically tells you that Alpha F times I F is same as Alpha atoms I R naught and that is basically q A D B by L V times P B naught by sin hyperbole x.

So, this is the term here exactly this same term. And this also you can understand from the if you consider a situation that if you apply a current year the current comes here if you apply current at the second term the current comes here there should be same basically at least for a symmetrical circuit. So, finally what we can do we can write IES I F naught exponential q V B by kT minus one minus reverse gain times I R naught.

So, this is basically a forward diode and this is basically the reverse diode. So, this is I R naught diode this is I F naught diode and then there is a current Source here there is a current Source here this is the meter this is base and this is collector. So, this is basically the model that is given by ever small and it is applicable for BJT last signal model for up to first order effects it does not consider the second order effects.

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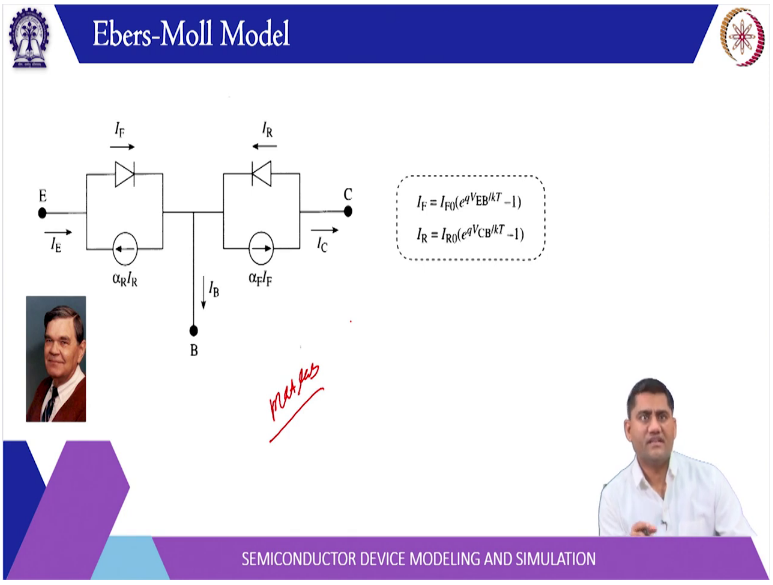

So, this is very simple model and you can replace you can write this equation maybe write a Matlab code ok to get the front IC BC curve or IV DB curve. So, different characteristics for the Mosfet for the BJT can be obtained using this model. So, this is basically coming from solving the meiotic carrier diffusion equation in case of BJT with all the assumptions that we have stated.

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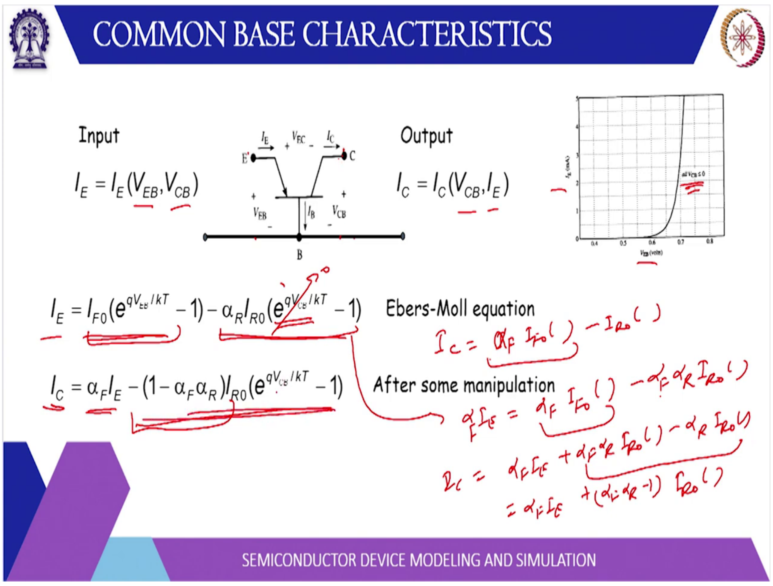

Now for common base the input is at the emitter and this input current has to be expressed in terms of V E B that is our input voltage and V C B that is the output voltage. Similarly at output current IC can be represented in terms of V C B the output voltage and the I E input current. So, I straight forward we can write from the Eber Moll equation that I is equal to I F naught minus Alpha R times I R naught I C if you recall this I C is equal to I Alpha F times I F naught exponential minus I R naught and then exponential.

So, I C is this term here now we have to write I C in terms of I E. So, what we can write this is the equation for I E we can write calculate Alpha I E. So, this is Alpha and Alpha F I E. So, Alpha F I will be Alpha F times I F naught exponential minus Alpha F Alpha R times I R naught times exponential I C S this term Alpha F times I F naught. So, this is same term here. So, I C can be written as this term. So, this term is basically Alpha F I E plus this term two to the left side.

So, Alpha f Alpha R times I R naught exponential and the second term is minus Alpha R times I R naught exponential. So, now we can combine these two. So, this is basically Alpha F times I E then plus Alpha F Alpha R minus one times I R naught exponential term. So, this is the thing here. So, I C can written as Alpha F times I then plus this term and this term we called I CBO or I C O you see here this is called V I CO.

Similarly we can write the equation for the common emitter but if you plot it I E versus V E B. So, and because then if V C B is reverse bias so, this will basically simply a diode equation and this is basically regardless of E C B because V C B is a reverse bias. So, this will be close to 0 actually. So, this is very small number. So, your I is simply a diode location and which is not affected by the base collector voltage and for I C this I C you can draw is plotted here IC versus V CB so, I C versus V CB.

So, ice is Alpha times I it is determined by I and if you change this VCB voltage this term is again quite a small because V C B is very small reverse bias. So, it will goes to 0. So, this is one minus one. So, e to the power 0 means one. So, one minus one is 0. So, this term will get becomes get neglected.

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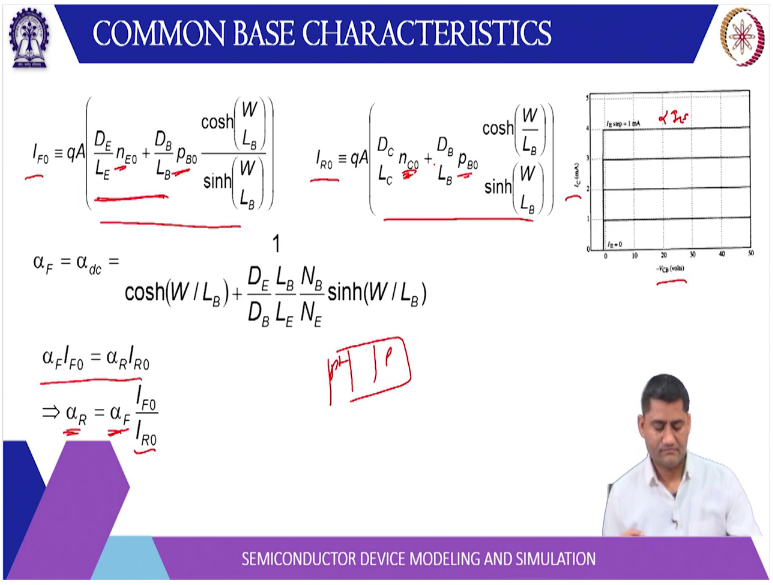

So, this is constant. So, I E is constant. So, this is I C is Alpha times I E you can set and then of course if you compare these different parameters I F naught I R naught with the equations we have derived. So, this will be the expression for I F naught and I R naught and Alpha f and you can also relate Alpha F and Alpha R because Alpha F I F naught should be equal to I Alpha R times I R naught.

So, Alpha R will be Alpha F times I F not by R naught you can notice one more thing here because alpha S F is close to one. So, Alpha actually will be small smaller than one because the emitter doping is large this is P plus this is P. So, Alpha F will be more Alpha R will be small and you can compare this I F naught and I R naught. So, if you look at this equation from the diode perspective the doping is larger in case of emitter.

So, this P B naught will be large n e naught will be small. So, this component will be larger in case of collector the doping is not dead large but is small. So, n c naught will be more but this P B naught will be P B naught is same in both the cases whether it is collector or emitter site. So, your I R naught will be actually should be more basically because this n C naught is not because of less doping.

So, Alpha R will be less than Alpha F. So, the reverse saturation current is more here. So, Alpha R is less than Alpha F by design. Then common emitter characteristic we use the same equation for I E and I C and your I B is equal to I E minus I C. So, this is basically I E is I F naught exponential minus Alpha R times I R naught exponential minus I C is Alpha F times I F naught exponential minus. So, minus minus become Plus I R naught exponential.

So, that basically comes out to be one minus Alpha F times I F naught exponential Plus 1 minus Alpha R times I R naught exponential term that is exponential minus one also. So, this per minus Alpha F I F naught one minus Alpha I R naught will be separate out and because this is exponential q V E B by kT and this is exponential q V C B by kT. So, if we take q B by kT outside. So, this is q V B by kT and this is q B C by kT. So, this is basically V E B minus V E C is equal to V C B.

So, it is written like this now from this we can evaluate this expression q E B by kT and that will be I B plus this term. So, I B plus this term divided by the coefficient here divided the coefficient here that is exponential q V B by K T. So, this one is exponential q V B by getting. So, your I C is Alpha F times I F naught minus I R naught exponential minus V C By kT times exponential q V B by kT plus I R naught minus Alpha F I F naught.

So, this basically little bit algebra is there you can find out. So, here we have expressed i c in terms of input parameter which is V E B and output which is V E C. So, we have removed B C B because in common emitter configuration input is at the base emitter output is at The Collector and emitter. So, we are not directly applying the V C V voltage rather we are applying V E B and V C E so, it is written like this.

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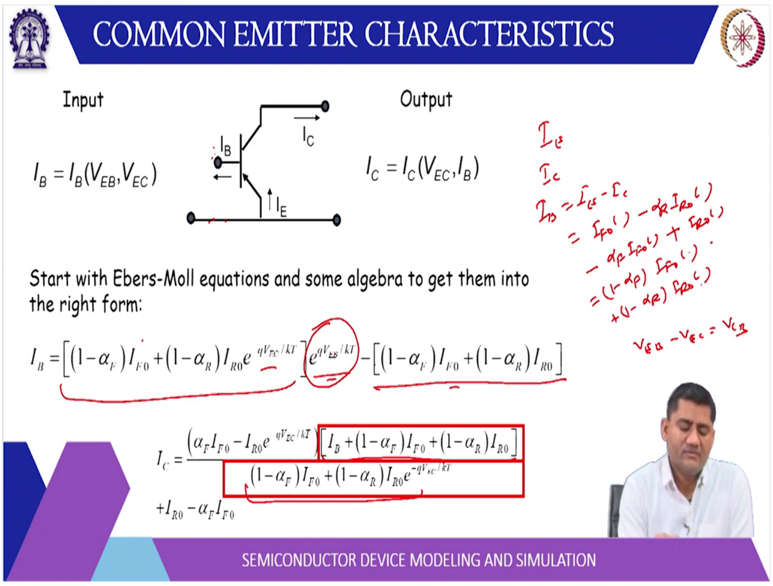

And if you plot this characteristic so, your I B versus V E B as you change the V E C if you change the V C here because V C is not small it is significant. So, this term will change basically. So, for higher V E C the current will decrease and that can be understood like this the current acting diameter. So, if it is not going to a collector it will come out to the base basically and the I C versus V E C is again constant.

So, that is expression for I C this is the expression for I C. So, I C is Alpha F I F naught minus I R naught q B C by kT times this term plus I R naught minus Alpha F I F naught.

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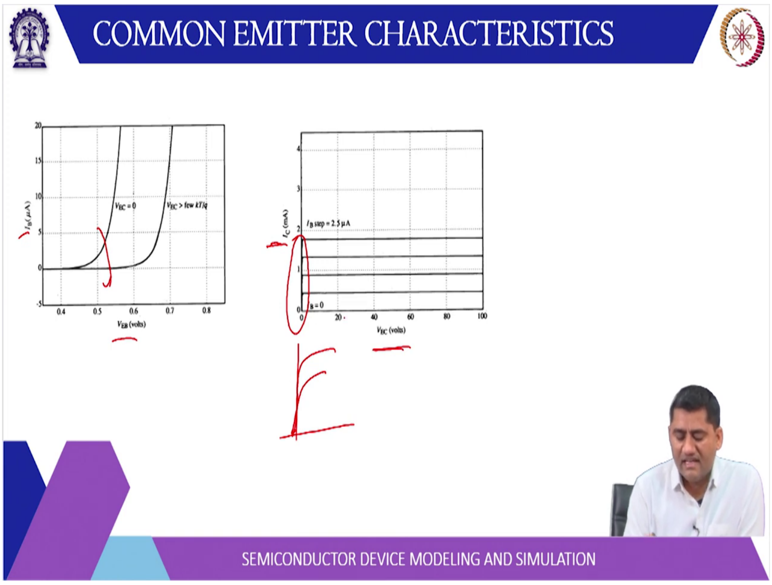

So, your I C basically is a constant with respect to V E C but if you notice here at a small V E C this is basically if you zoom it you will get some curve like this. So, that means there is some reason here where it grows basically it is not Alpha times I E or beta times I B at 0 V C but in case of common base if you recall this is sharp. So, at 0 it is already Alpha times I E. So, there is a difference that you can notice. So, these were the characteristic for the common emitter and common base diodes.

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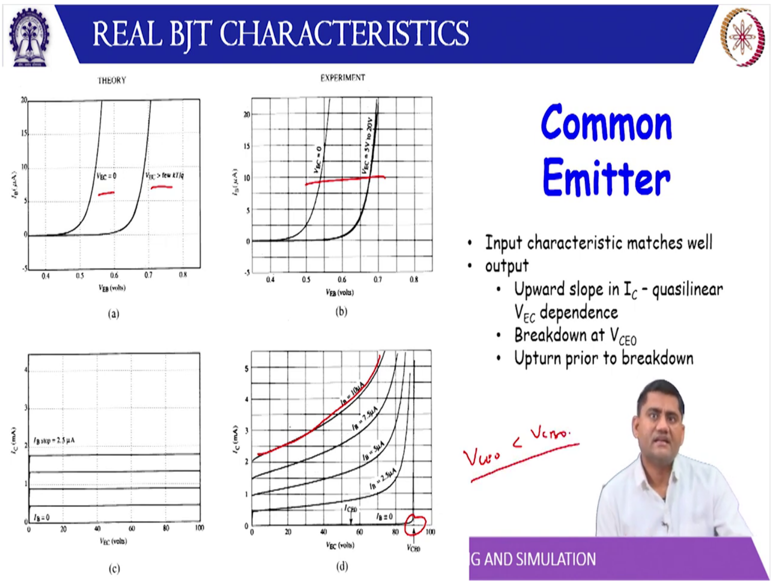

Now if you compare theoretically calculated versus the experimentally calculated as we projected in case of common ways V C B regardless of V C B, I E was same but that is not the case actually if you increase the V C V to a more reverse bias the current Actually I E current actually increases and there is a reason for that we call that base weight modulation and another thing you can notice here this I C versus B C B is not constant at certain point it has to basically some breakdown will occur in case like in case of BJT.

So, that breakdown voltage here is around 120 and we call it V C BO. So, it is constant then at V C U it actually increases. So, that is the breakdown phenomena same as the P-N junction diode. Similarly in case of common emitter the input characteristics are similar not much different output characteristic there is a difference there two differences here one this I C versus V E C is not constant but it is sub linearly increasing.

And at certain point around 90 volt this again breakdown takes place. One more thing you can notice here that V C B O is around 120 and V C O is around 90. So, that means V C E O is less than V C V O. So, the breakdown voltage for common emitter is less compared to the common base.

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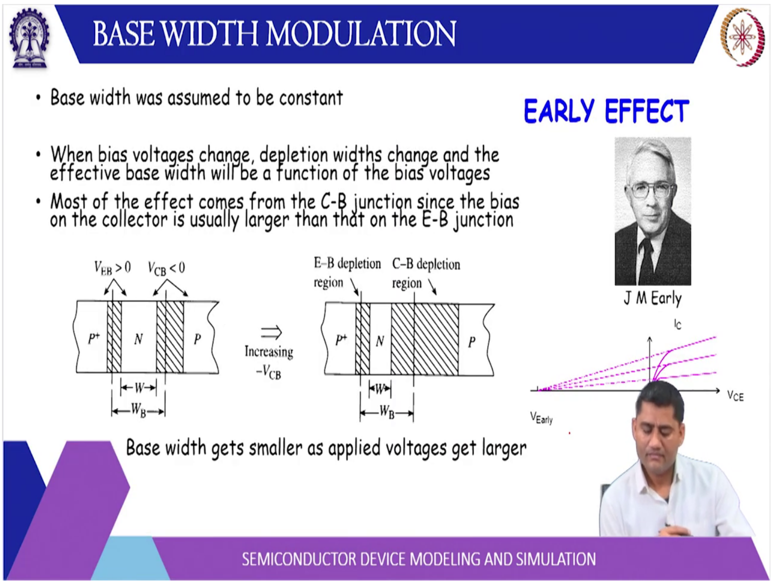

So, these two phenomena have to be explained. So, in the model in the beginning we assumed this base width was constant but your base character is forward bias. So, the depletion width for the base collector base emitter Junction is usually small. So, it is not a point of concern but the base collector is reverse biased. So, here the base collector Junction depletion width will increase especially if you increase the reverse bias.

So, what will happen you know the base width the effective base width will reduce and if you think the carrier profile like this. So, if the base width is reduced then this slope will be more. So, then this current will actually increase. So, this is this is what is happening so you can see I C versus B C. So, as the V C is increasing this ice is increasing because this width is less therefore the slope is more and therefore the diffusion current is also more.

So, both I C and I actually increase and we can calculate this depletion width using the formula that we drive for the P N Junction and you can actually you know write a simple Matlab program ok to see this effect. So, include calculate the depletion width and write this W that as a W B minus some x j on emitter side minus x j on collector side. So, this is x j on emitter collector side this is x j on emitter side.

So, if you substitute W by this expression in the expression we have derived we will get the modified currents.

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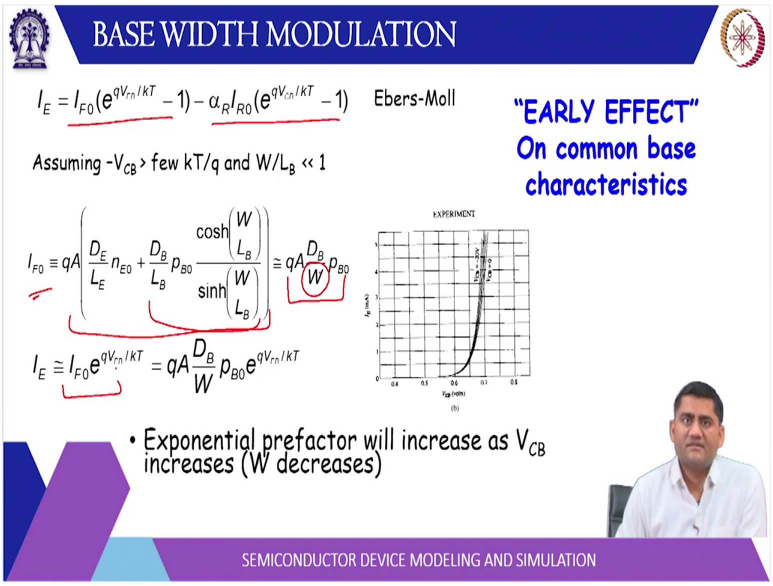

So, as far as analytically it is concerned your I is i f naught exponential q V by kT minus one minus inverse transport reverse transport which is IR I Alpha times i r naught exponential q b c by kT minus one. And if you recall that I x naught is q A times D E by L E times n e naught plus D B y L B times P V naught cot hyperbolic W by L and because emitter is highly doubt. So, the second component actually dominates.

So, it can be replaced by q a times P B times and now this is cot hyperbolic W I L can be written as one over W by L. So, L will cancel. So, this is one by W. So, now this W is coming into the denominator. So, this pre factor is actually increasing. So, the pre factor of IE is actually increasing for higher base collector reverse biases. So, that is why this effect is being observed and it was invented by a scientist Early.

So, it is named after him known as Early Effect or name base weight modulation is more give you more information about the physical correct physical origin.

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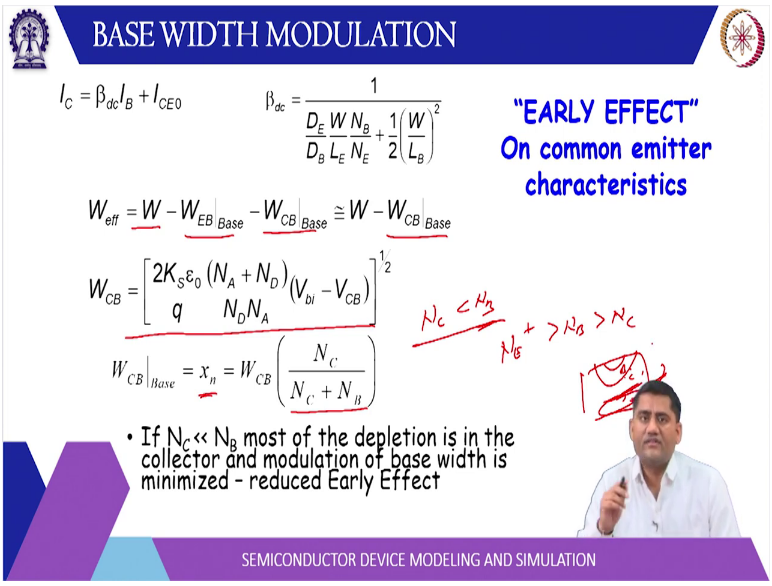

Now in case of common emitter also you can estimate the width of the depletion region. So, W is basically W the natural width of the base minus from the emitter side depletion region minus depletion region from the collector side. So, because emitter side is forward wise this is small we can consider the depletion weights on the collector side. So, actually in the base due to the base collector voltage and this is the expression you can recall from the diode.

So, your W C B is basically N C by N C plus N V now if you want to minimize the Early Effect then we would like this to be a small number. So, this will be a small number if your N C is less than N B. So, if N C is less than n v then the amount of depletion region that falls on the base side will be less because base is more doping. So, for higher doping side the depletion region is less. So, this is technique is used to basically reduce early effects.

So, generally what is done emitter doping is more than the base doping then the collector doping but if you have less doping for the collector then the resistance of the collector region will be high. So, what is done some kind of buried layer is created here inside the collector. So, that for contact we have less resistance. So, at the base collector junction the collector is a smaller doping. So, away from that junction again we have higher doping.

So, that at least for the depletion region it does not see a higher doping on the collector side and that actually minimizes or reduces the early effect.

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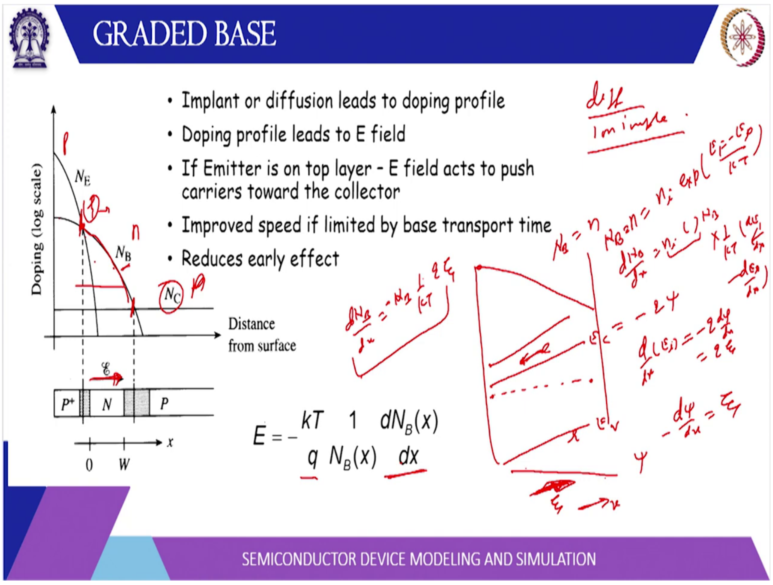

Another technique that is used or rather there are two ways of getting the the doping profile one is diffusion other is iron implantation. So, in iron implantation we can be more precise and we can control the dope and distribution profile in case of diffusion it is thermal thermally controlled process. So, we do not have much control on the profile because if you apply the heat treatment it will follow certain Gaussian or Winner function profile.

So, what happens if you look at the typical doping profile for the BJT. So, let us say we start with a semiconductor material with N C doping and that is uniform but during the growth we have a uniform profile then we dope it with let us say this is N type this is this is P type this is N type. So, we do a N type doping for N V. So, the profile is like this. Then on top of this we do again P type doping for emitter.

So, whose profile will be like this and where these both the concentrations are equal that is neutral. So, that means this side is P and this side is N. So, this is a junction. So, this emitter base junction similarly where the concentrations are equal this is a base this is a character. So, this is the base collector Junction. So, now you see in the base region the doping is not constant but it has a certain slope.

So, that means if you just consider the base region the electron concentration is decreasing like this if we assume that N B is equal to N. So, all the depends are ionized now if you translate that into a band diagram. So, because we assume the Fermi level is more or less constant here. So, when the doping is higher the number of electron is more. So, the Fermi level will be close to the conduction band.

So, let us see here and when the doping is less familiar is away from the conduction. So, you can think something like this still it is n type. So, you can something like this. So, this is your E C this is your E V. So, it is N type here but it is more N type on the left side less N type on the right side now this is the energy which is minus q times the potential PSI. So, you can find out the PSI from here is basically something like this is decreasing the potential is decreasing.

And the derivative of potential d PSI by d x with minus sign is the electric field. So, electric field is d PSI by dx if this is x Direction. So, d PSI by dx is negative. So, that is electric field is in this direction dc by dx is negative right. So, minus will be positive sorry it will be in forward Direction ok and PSI is decreasing. So, d psi by dx is negative. So, minus d psi by d x is positive. So, and another thing you can see if you put a hole here and if you put electron here electron will go down like this.

So, electron moves always in the opposite to the electric field. So, you can see that electron will naturally move to this side. So, the electric field is in positive x direction. So, electric field is in positive x direction here now you can relate it with the doping concentration if you recall the expression N is equal to N I exponential E F minus E I by kT. So, if all that opens ionized. So, you can write N B is equal to N and if you take the derivative dN b by dx is N i exponential.

So, this will be there. So, you can write simply n here or n v here times the derivative of this. So, one over kT times dE F by dx minus dE I by dx if Fermi level is constant this term goes to 0. So, dE I by dx is d by dx of E I, E I is minus q psi so, minus q d psi by dx. So, this is basically q times electric field. So, you can write it as D n B by dx is equal to N B times 1 by kT times q times electric field.

So, you can get the expression for reactive field from here. So, electric field will be kT by q 1 by N V dN B by dx there is a minus sign here did we miss something dy dx is minus this. So, plus q is minus here actually. So, this is one now. So, electric field is negative of dN B by dx is a negative gradient of dN by dx. So, this is decreasing. So, electric field is in a forward direction now from emitter holes will be injected to the base.

Now these holes will be assisted by this electric field. So, that means if it were a uniformed open then holes would move only under the influence of diffusion profile or under the effect of concentration gradient but now their speed will actually be more because they are moving due to two things the diffusion profile the concentration gradient as well as they are assisted by the electric field. So, this this graded base also improves, improves the speed of your BJT transistor.

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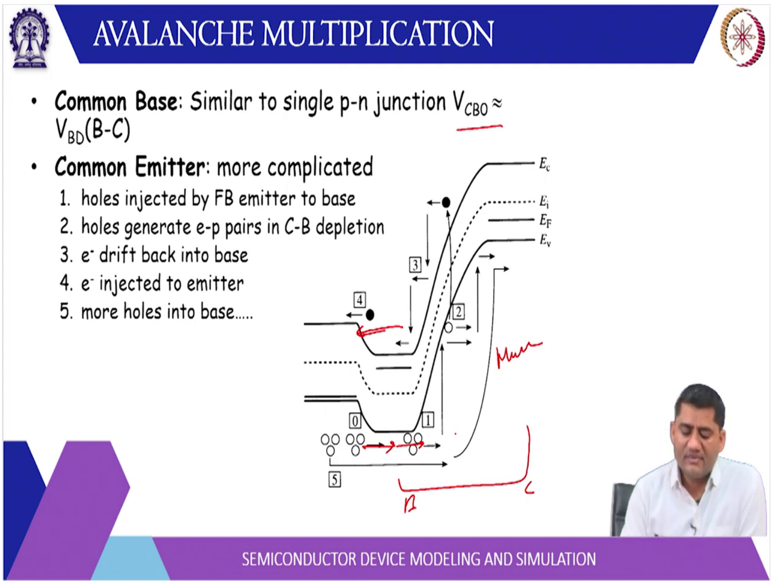

Common secondary order effect we can see the breakdown phenomena. So, we have already discussed a breakdown phenomena in case of PN Junction. So, when PN Junction is Zero's bias. So, this is a base collector Junction it will break down a certain voltage. So, that is for the common base and we call it V CBO that will be same as the breakdown of this base collector junction in isolation but in case of common emitter.

Now the process is more complicated or rather more interesting these holes they move from the emitter to the base and most of them actually go to this base collector junction now when we they go to the base collector junction the multiplication takes place. And when they multiply then holes move and the electrons come here and these electrons again move to the emitter region then more holes will come to the base region.

So, it is basically getting a some kind of feedback from the emitter. So, this multiplication get further enhanced due to the supply from the emitter. So, breakdown actually takes place at a lower voltage.

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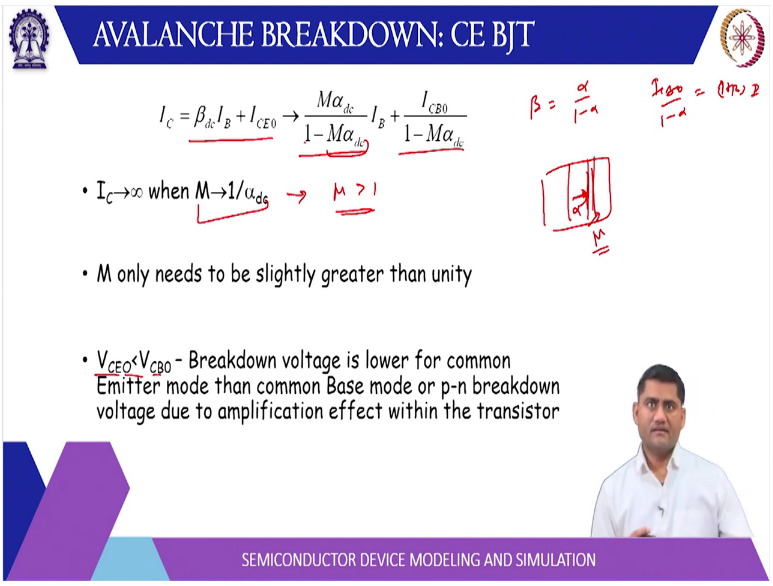

So, if you recall the expression for I C is beta times I B plus I CO and beta is Alpha over one minus Alpha and Alpha is the base transport factor now what is happening here Alpha is a base transport factor and then at this reverse bias under breakdown this is a multiplication. So, what is happening here you instead of alpha you are getting m alpha. So, if you replace this Alpha by m alpha.

So, your beta will be replaced by m alpha by one minus m alpha times I B plus I CO is basically I CBO by one minus Alpha. So, that is or it is one plus beta times I CBO, so, one minus I CBO one minus m alpha so, now this m alpha as to be 1. So, that means your M should be one by Alpha now Alpha is less than one. So, it actually requires that M should be slightly greater than one.

In case of standalone base collector junction M as M was required to be high enough but when emitter comes into the picture now m is required to be slightly greater than one that is it. So, the V CO the common emitter breakdown voltage is smaller than the common base breakdown voltage due to this amplification effect.

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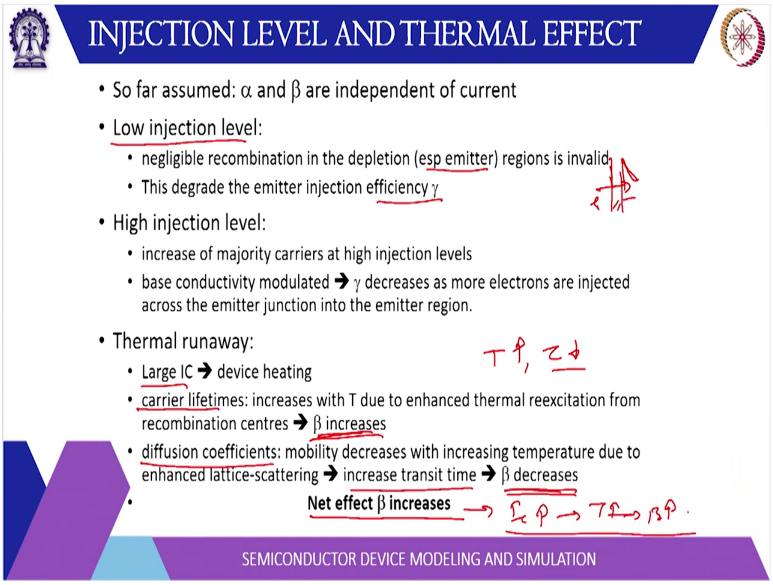

There are some other ah considerations similar to the PN Junction diode we can see here at low level injection because in the derivation we assume that in the deeply region there was no recombination generation and especially at the base emitter junction because this is forward bias. So, there will be some recombination and that will degrade the emitter injection efficiency because the holes that are coming from the emitter.

They are not all reaching to the base but they are recombining in the depletion region and at high injection levels the majority carriers are actually much higher means they are more than the doping level. So, this basically modulates the base conductivity and because more number of elect more number of carriers are injected from the both sides emitter as well as the base. So, this enters into the non-linear region and there we have different expression for the base current and the emitter current.

Another is at large current or large I C there is some heating effect. So, there is a temperature will increase now this temperature tends to affect beta in different ways if you consider different phenomena if you consider carry a lifetime. So, as the temperature increases carry a lifetime will decrease because now there will be more number of collisions so, if tau is less your beta will actually increase.

Similarly if you consider diffusion coefficient so, if temperature increases there is more diffusion. So, that means the transit time will be more now because these carriers that are going through the base they will experience enhanced scattering and that will decrease the beta. So, there are two competing things here due to one reason beta increases due to another reason beta decreases.

So, among these two phenomena the dominant phenomena is basically this carry a lifetime and change in the carry lifetime. So, net effect is basically that beta increases and because beta increases i c increases an ice increases temperature increases temperature increases again beta increases. So, that is basically curl thermal runaway.

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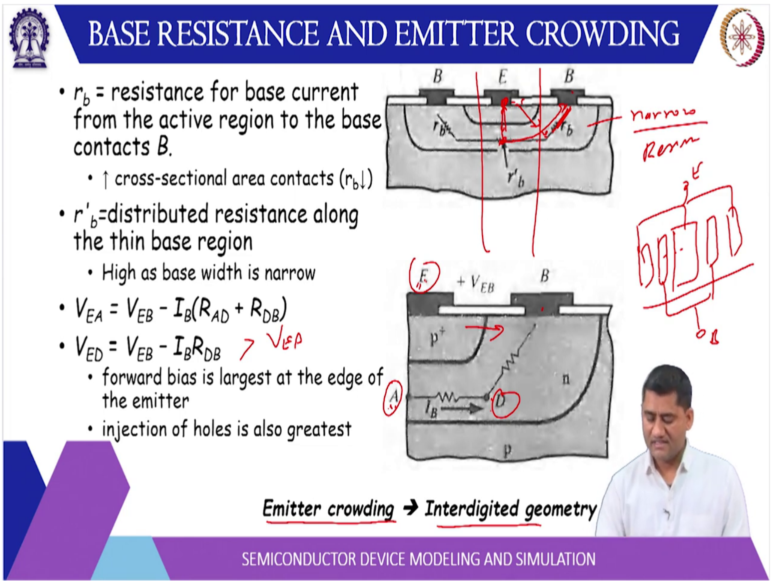

And another phenomena is the base resistance because base is actually narrow here and is doping is limited it cannot be as high as emitter. So, it has some resistance and if you see this region the cross section region here it is away from the base contact. So, the base current actually has to travel something like this. So, there is a base resistance and there is a base spreading resistance. So, the potential difference between these two terminals and these two terminals is different.

So, the potential difference here will be more than this region. So, at the edge base emitter H there is more potential difference because as this part carries move potential drops here. So, the difference here point we call it this point let us say this point is A this point is D this is E. So, the potential between E and A is less compared to e and D E B is the applied potential and it further drops at D further drops at A.

So, your V E D is more than B E A. So, forward bias the largest at the edge. So, obviously more current will flow at the edge and that is called emitter crowding. So, the solution to this problem is interesting geometry. So, that means you have just base reason here then your emitter region here then base region here. So, make multiple contacts. So, because at the edge there is a current flow and we have this multiple contact here. So, these are basically you can something like this you can say.

So, one side will be base one side will be emitter. So, now that problem can be overcome because now this effect is distributed over multiple contacts.

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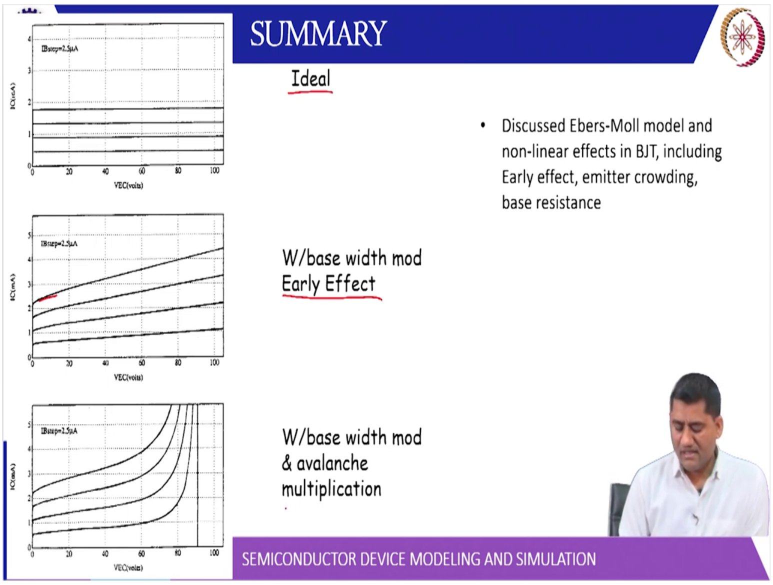

So, in summary we have discussed the Ebers Moll model and we drive the condition that I C versus V EC is constant for ideal when it includes the base width modulation or early effect it actually tend to increase sub linearly and then if you include the Avalanche effect. Then some this breakdown can be observed at certain voltage and then of course we have discussed other parameters like emitter crowding and the base resistance effect, thank you very much.