Semiconductor Device Modelling and Simulation
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Lecture – 20
Bipolar junction Transistor

Hello, welcome to lecture number 20. Now today we will discuss about bipolar junction we have already discussed about PN junction we have this we derived the IV current equation for a P-N junction then how this ideal IV characteristic for a P-N junction deviate in real scenario. So, we consider all those cases now we will discuss about the bipolar junction transistor. So, transistors are basically 3 terminal devices these are 3 terminal devices.

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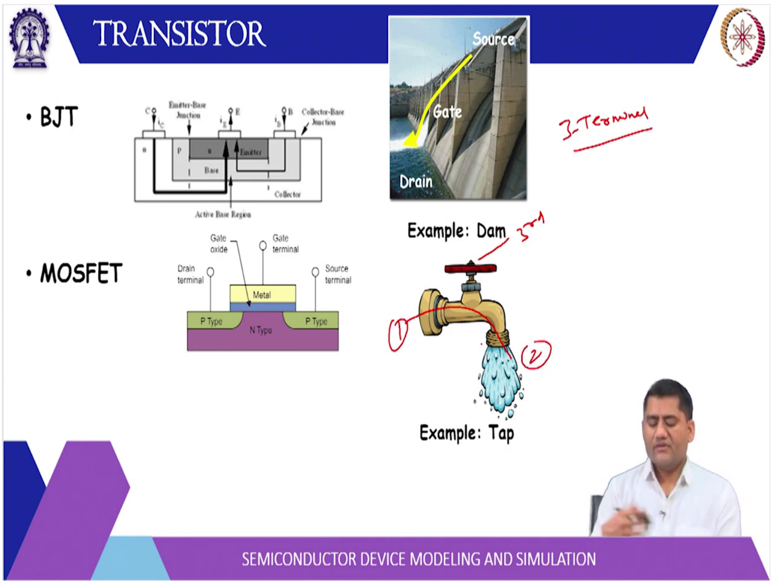

It is something like this a third terminal controls the current flow between 2 terminals. So, you can take example of tape right you on this knob then more water can flow and so on or you can see a dam if you open the gates of the dam to the extent the gates are open the water will flow same properties is used in the transistor. So, we will discuss 2 transistors basically 1 is the BJT other is the MOSFET.

BJT is called bipolar junction transistor that means both the carriers take part in the current conduction bipolar means both electron + hole junction transistor through the junctions we achieve this transistor action. So, applied bias at certain terminal called the base emitter terminal determines the current flow through the third terminal at the collector or is called collected and emitter current.

In case of MOSFET these are unipolar devices. So, the gate terminal will attract the carriers here if attract these electrons here then they cannot flow because these 2 ends are P type. But if attracts if it attracts the holes then the current can flow and then channel is as established and the current will basically flow through this channel that is below this gate. So, we will go 1 by 1 let us consider bipolar junction transistor.

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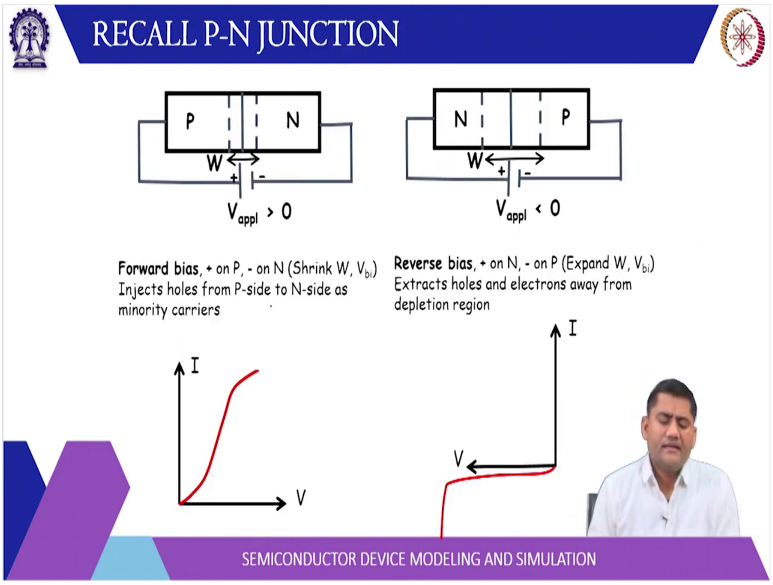

It consists of 2 P-N junction connected back to back. So, let us consider there is a 1 P-N junction which is forward bias there is another P-N junction which is reverse bias. Now in case of forward bias PN junction a lot of current flows because holes are supplied from here electrons are supplied from here and they are in majority. So, lot of carries are available and the current will flow in case of reverse biosphere junction this is positive.

So, it will supply the holes this is a negative it will supply the electrons but these electrons are in scarcity here. So, we will not achieve the current although there is a Fermi level difference this there. So, is there a way we can inject holes here. If you look at this Ferro noise PN junction what it is doing it is injecting these holes to the N side and then we merge these 2 it is possible that this hole can go through.

But wait a second if you connect them through a wire or if the length is long enough this hole will recombine with the electrons and hardly any hole will reach here. So, again it will be basically a reverse bias junction with no current but if we make this junction a small or a small thickness then these holes will cross over to this reverse biosphere junction and they will constitute the current. So, that is a fundamental theory behind the bipolar junction transistors.

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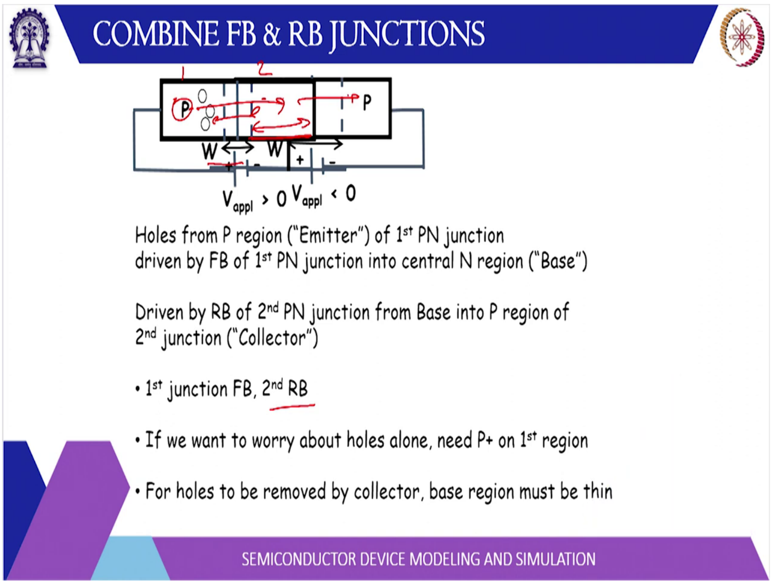

So, you can see here when they are combined and if this width is small then the holes injected from here will cross over. So, first junction is power wires second junction is reverse bias and these holes injected from the forward wise junction constitute carrier for the second reverse bias junction. So, of course there are some requirements because if holes are injected from here then there should be more holes compared to electrons.

Because electron if go from here to here they will not contribute to other tarnish direction only the holes that are moving from reserve 1 to region 2 will cons will be part of the transistor action. So, that means this region should be more doped and then they should be quickly cross over this base region that means this base region should be narrow so, that they are easily collected by this terminal.

So, in BJT term we call this one as emitter because this is emitting the carriers and this is the collector. So, this is collecting the carriers and this is called base. So, these carries are transiting through the base.

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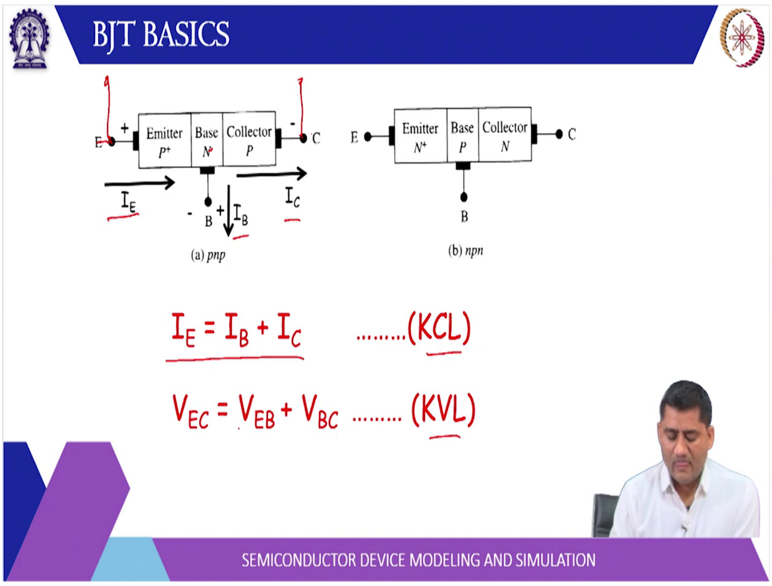

Now let us look at the some of the terminologies. So, emitter current I E is the current entering the emitter terminal I C is the current exacting the collector terminal I B is the current exiting the base terminal. So, if you apply simple KCl which is sketch of current law then I E the current entering is equal to current exiting that is I B + I C. So, this is 1 relationship. Another using the Kirchhoff's of voltage law V EC the voltage between these 2 terminal is V EB + V BC. So, V EC's V EB + V BC so, this is 1 basic relation that we should remember.

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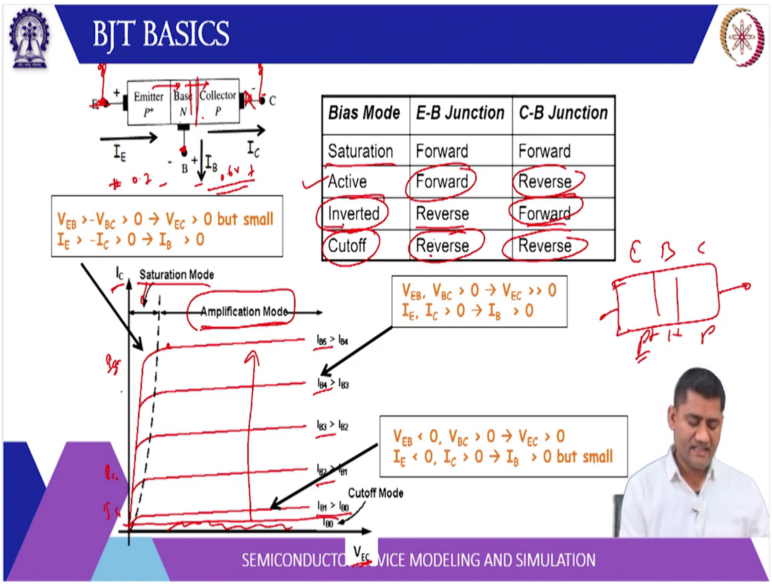

Then how to reach the characteristic curve for BJT now in case of P-N junction there are 2 terminals. So, we have got 1 curve basically we vary the voltage and we very get the current and vice versa. In case of BJT there are 3 terminals. So, what we will do we can plot this current versus or I E versus voltage so, I E versus V V, I versus V VC I C versus V VC, I versus V CE. So, there are different possibilities.

So, 1 popular method is basically we plot the collector current versus V CE voltage across emitter and collector. So, now these are the 2 terminals ok and we want to find out what is the current I C. So, I C current is moving out time. So, I C current as a function of the voltage across these 2 terminal is determined by the third terminal which is like a knob of the tap. So, the temp is the water is flowing; these 2 terminals and this base is basically kind of knob.

So, if base current is small or base terminal is open let us say then I B is zero then no current actually flows because there is a reverse bias junction. Now if we connect some small bias across base animator then this is forward bias then some current will flow through and some holes will go to the base and they will be collected by the collector. So, the current will increase. So, as the base current increases the collector current increases.

So, I B 1 I B 2 I B 3 I B 4 I B 5 then this is I C 1 I C 2 this is I C 5. So, this basically increases basically. So, this is called amplification mode or it is also called forward active mode when V EC is small. So, this voltage is small. So, here this region is called the saturation mode that will come at evident when we go at with the discussion. So, these are different configuration that you may encounter in case of BJT.

So, for BJT function thus base emitter has to be forward wise if the base emitter is reverse bias then this is used as basically it will not conduct as far as current flow is concerned. So, when base junction is reverse bias then this is cut off but wait a second what about emitter the collector and base. If you look at this BJT this is emitter this is base this is collector. So, this is p + n and p it is also possible because it is if the device is symmetrical this collector may act as emitter.

And the emitter may act as a collector that is possible because this is also p and p although when it is designed emitter doping is much larger. So, the using emitter will be less efficient. So, if this emitter basis junction is reverse bias but collector base is forward bias it will operate in inverted mode. So, that is the inverted mode. So, when both the junction are reverse bias it is cut off when base emitter is reverse and base collector is forward it is inverted.

And when base emitter is forward base character is worse it is forward active mode and when both are forward wise it is called saturation. So, fertilization is like this let us say this is also 0.7 volt this is also let us say 0.6 volt plus minus. So, this is plus this is minus this is plus this is minus. So, this is paralyzed with 0.7 volts. So, this emitter will send the holes here but this is also for advice.

So, the field is less here because this formula is not reverse bias. So, its collecting capacity is less. So, although holes are coming here but all are not actually collected. So, that is why you have the saturation rear region where the current is basically is not a constant it is linearly changing in this region. So, in the figure you can identify this is cut off region below certain current base current where this is base emitter is reverse bias. Then this is forward active mode which is also called amplification mode.

Because in this mode BJT is used as amplifier because you apply small current at the base you get a large current at the collector and then this is the saturation mode. And inverse active mode or inverted mode will by in our other because V EC will be you can calculate it because base emitter is reverse bias base collector is forward wise. So, a sign will change basically and the current direction also usually you know the in between another quadrant.

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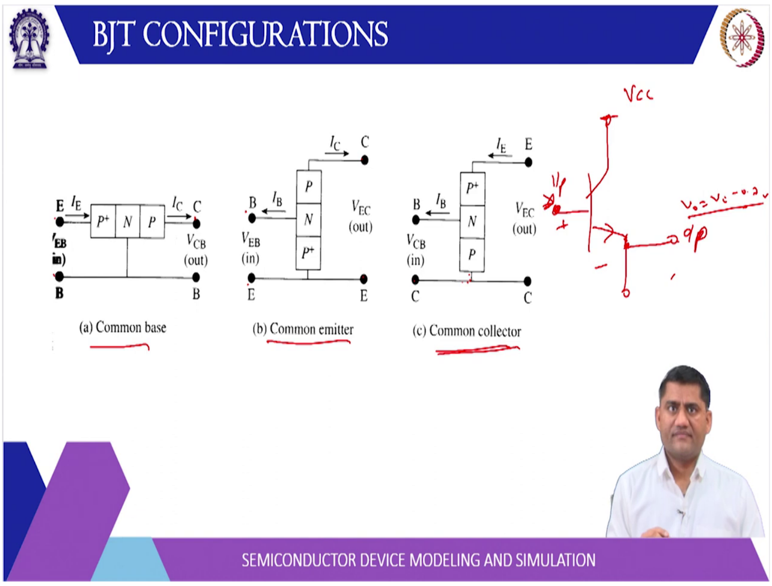

Now different configurations of the BJT that are used in practice 1 is common base. So, where base is common the input is applied at the emitter and the base output is across collector and base. So, this is called common base. Common emitter input is across base and emitter output is a cross collector and emitter. So, this is common emitter and common collector input is across base and emitter sorry input is across base and collector and output is taken across emitter and collector you can look at like this.

So, this base meter junction is always the controlling term ok. So, if you apply a voltage here then what you will get you will get measure the voltage here ok. So, this will be the input at the base and output is here. So, this collector is basically applied to certain V CC high voltage there ok then when it changes input voltage the output actually follows the input so, because there is a difference of 0.7 only because this diode is forward wires.

So, V out will be V in minus 0.7 volt so the advantage of this circuit is basically that it has the same voltage as the input with a difference of 0.7 but it can supply a large current. So, here circuit according as per the circuit it appears that it is common collector because input is at the base and output is at the emitter. So, in this way it is common collector it does not mean that collector is grounded. So, this is not grounded here in other case it can be grounded.

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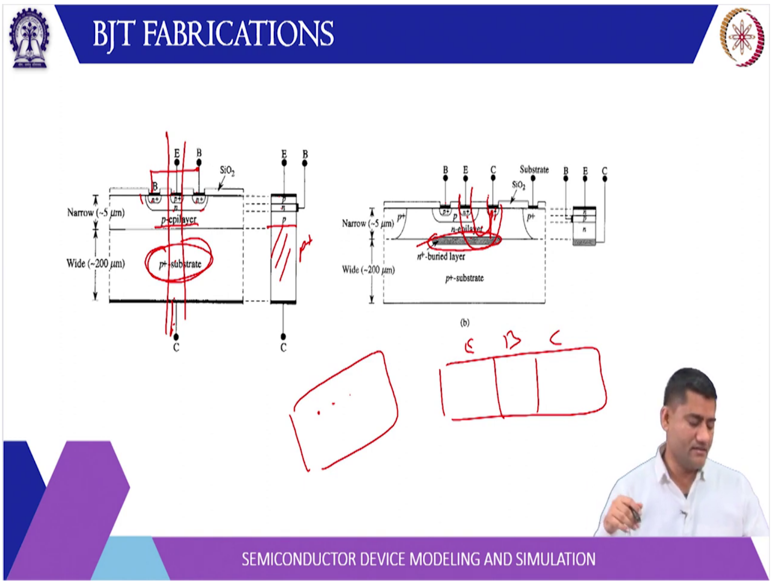

Now generally we represent BJT like this. So, this is the emitter this is the base this is the collector. So, this slide is basically just to show you that actual BJT does not look like this. Actual BJT is a little bit more complex. So, if you can look here this is a substrate P + substrate then on which P type epilator is deposited then in that region there is a n well that is formed and in the end well you have P + emitter n + base and N + base.

These 2 base are basically connected together you know they are connected together and this is the emitter. So, emitter is P type bases N type and then collector is also P type. So, the connection can be taken from here or it can be taken from the top. So, if you look at the cross section for this region P + N P. So, P + N P and this is this P + actually purpose is to reduce the resistance.

So, if it is p + then the resistance of this region will be less. So, there is no drop across this region not significant drop another way is basically the people use this buried N + layer. So, this is the purpose of this layer is also to reduce the resistance and then again make a contact through certain. So, here is a the contact is made on the top because in planar technology we would like to have this context on the top rather than on the back side especially when we record to the integration of these different devices.

So, again if you see here it is not that straight forward but its look like this see. So, N + P and then N +. So, this is the collector region which is a small Dot and then N + all the contacts are done with the high doping the purpose for height opening is that. So, that the contact is ohmic because at less doping this contact may act like a rectifying contact so, that we will discuss in coming lectures.

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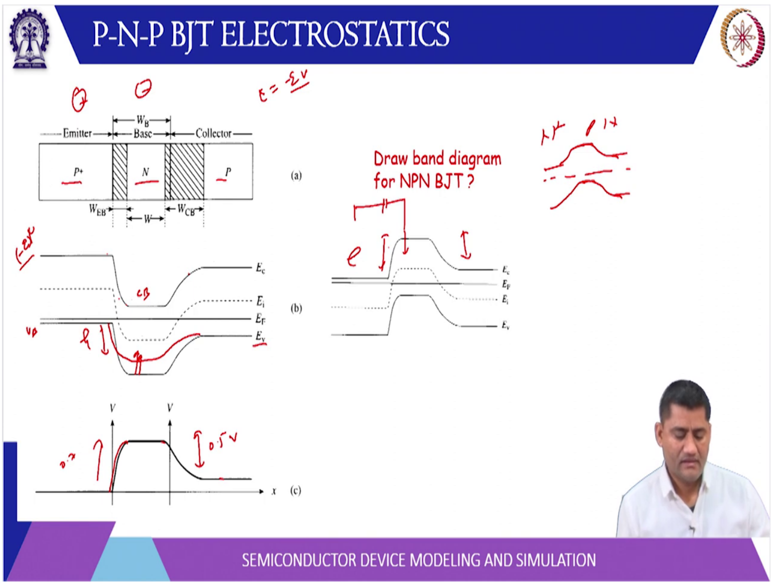

Now it is very important to draw the band diagram because band diagram tells you how the device will actually function. So, if you look at the BJT P + N and P and at equilibrium when the bias is applied or this zero then the permeable has to be constant. So, P + the Fermi level is close to the valence band and ferment is close to the conduction band again P permeable is close to the balance band and then this permeable if it is constant then other bands will accordingly change.

So, here it will go down. So, that means the potential this is energy right. So, minus q is the charge on electron times potential. So, this energy minus q psi, so, psi will actually this is decreasing psi will increase and then here it is increasing. So, I will decrease. So, now there is a difference here this is V bi for this junction this is the V bi for second junction. So, this is typically around 0.7 because there is high dropping here this is around 0.5 volt because here the doping is little less.

Similarly you can draw the band diagram for npn. So, if you have a some N + P-N right. So, this is the Fermi level. So, N + conduction band is here for p conductor wind is here and again n. So, conduction but it is slightly above right. So, it will again look like this. So, this is the built-in potential at emitter base junction this is a built-in potential at collector based tension. So, now you can see here 4 electrons this is the barrier.

So, when you apply the base emitter bias here you lower this barrier basically for holes this is the barrier. So, when you apply the emitter base bias you lower this barrier. So, that more current can flow you see this is positive this is negative. So, when you apply positive voltage here. So, high potential means energy will be lowered negative potential means energy will be increased so, because energy is minus q times V.

So, here energy will be reduced this energy will increase. So, this will go up basically because energy is now more. So, for applied bias it will look something like this. So, now holes have a smaller barrier here. So, more holes can flow through this one and same thing for NP and BJT.

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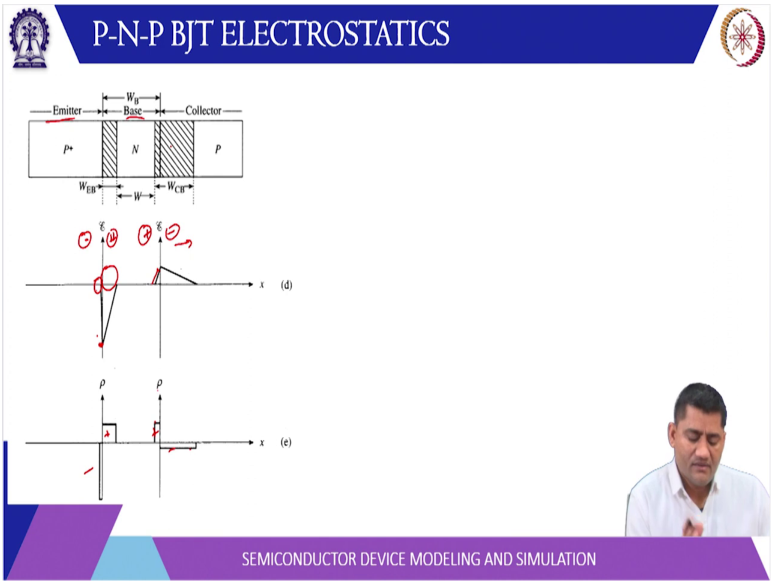

So, look at the PNP electrostatics. So, this is the base meter junction emitter base junction. So, emitter is usually highly doped. So, depletion is an extend less in this region more in base region. So, corresponding with the electric field electric field always peaks at the metallurgical junction. So, here is P + N. So, the charges are negative year positive charges are here this N D + this N A minus. So, the field is in Negative x Direction. So, the value is minus here N D + N A minus.

So, free relation point direct direction. So, it is like this so this is the charge distribution plus minus plus minus and this electric field plot. So, from this plot you can say that emitter doping is more than the base doping and from this you can see the base doping is more than the collector doping in this case. So, collected doping means the doping near to the junction not far away from the junction far away from the junction this high doping is used to reduce the resistance. But we are talking about the doping near the junction.

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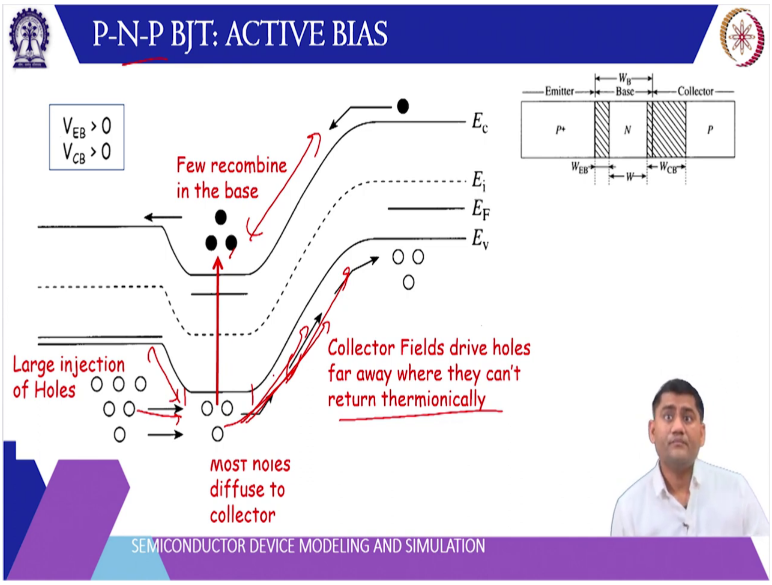

So, for PNP, BJT and the reactive bias when the base emitter is forward bias base collector reserves bias. So, when base emitter is forward biased this barrier is reduced. So, more hole can go in and here this biases reverse bias. So, this barrier is even higher right. So, this is the barrier for these electrons but when holes are getting injected and they do not recombine in this region or that means base is narrow these all can go through this is the transistor action.

So, this most of the hole diffuse to the collector and collect basically collector collects them and this High field actually drives them. So, via the field is better because these holes will be accelerated and they will quickly collected.

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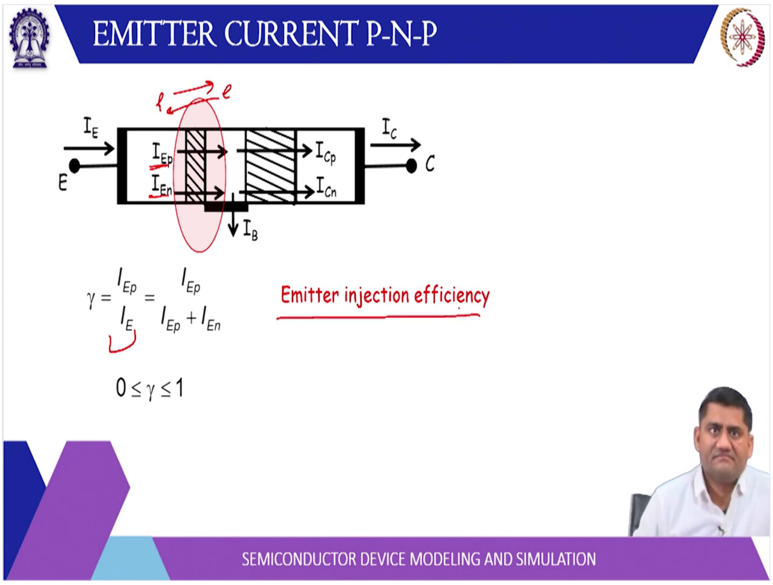

So, this brings us to the you know to the concept that at the base emitter junction when it is followed by us the current at the emitter can be thought of due to 2 components 1 is holes moving or getting injected from the emitter electrons coming from base to emitter. So, we call it this as I EP due to holes and we call it I EN due to electrons. Now we want more current due to the holes because holes are the carriers that are effective in transistor action because these holes will go and cross over and collected by the collector.

So, the ratio of this I EP to the total I E the whole current divided by total emitter current that is called emitter injection efficiency at that parameter we would ideally like to have close to 1 but it can be somewhere between zero and 1 and it can be close to one. So, by design it should be close to 1 so, this emitter current.

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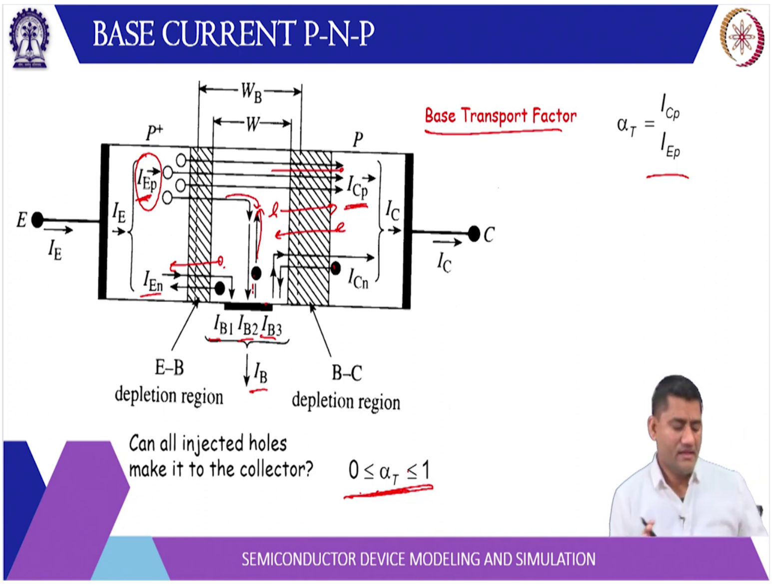

Now the base current you can think of the 2 components. So, the electrons that are moving from the base, so this electrons that are moving from the base to the emitter that is 1 component then some electrons are recombining with these holes that are coming from the emitter. So, these electrons have to be provided by the base contact. So, the electrons that are going to the emitter electrons that are combining with the holes in the base region they have to be supplied by the base.

So, this I B1 and I B2 are the base current and the third comes from the reverse bias junction. So, although holes are supplied by the emitter and they are collected by the collector but these are reverse bias junction. So, the holes will go from this to this side electron will go from this side to this side. So, these electrons will also come from the collector side. So, these are minority carrier current.

So, that reverse saturation current has also need to be supplied by the base. So, this the reverse sensational current at the reverse bias base collector junction so, these 3 components contribute to the base current. And now how many holes go through this base region to the collector that is called base transport factor. So, this I E is consisting of I EP + I N and this I EP going to I CP. So, rest are recombining here.

So, the ratio of I CP and I EP so, total number of holes injected by the emitter and the ratio of the total number of collected holes by the collector the ratio of 2 will give you the base transport factor. So, this again should be between ideally should be 1 because we would like to all the holes that are injected from the emitter to cross over the base and go to the collector region but it is between 0 and 1 and is supposed to be close to be 1.

Of course this Alpha T will depend on if base is narrow then there is a less time for these carriers to recombine. So, if you make the base narrow then this Alpha T will increase another if you reduce the doping of the base then the opportunity for these holes in the base region to combine with electron is less reduced right. So, if the base doping is reduced base width is reduced then of course we can increase the alpha.

But we cannot arbitrarily reduce the base but if you make it zero then there is no transistor action at all or if we make it very less to the base region then of course the depletion may extend all the way to the other junction. So, that will not be a good proposition. So, there are certain design limitation that we cannot go on increasing the decreasing the doping of the base we cannot go on reducing the width of the base. So, some reasonable value of the base dropping and the base weight we have to choose.

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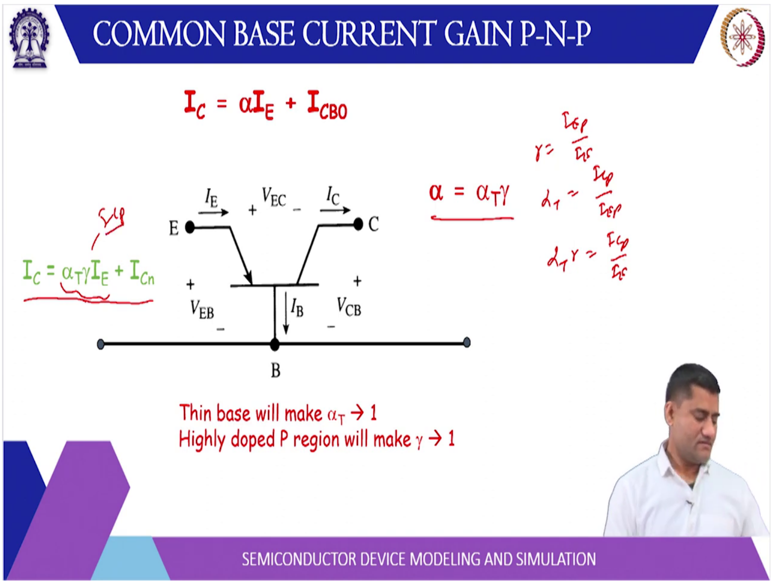

Now let us consider a common base and we already know that I E is equal to I C + I B and that is because we have defined that emitter current is the current diameter collector current and base current are the currents exiting these 2 terminals and I E consists of I EN + I EP I C consists of I C p + I C n I C n is very small so, its mole I C p. So, the ratio I C p by I E is Alpha. So, you can write this alpha s the product of emitter injection efficiency that is gamma times base transport factor Alpha T.

So, if we make this gamma and Alpha T close to 1 this Alpha will also be close to one. So, this Alpha is Alpha T times Alpha is Alpha T times gamma and. So, you can write ICS Alpha T gamma times IE + I C n. So, this is I C p + I C n and if you recall gamma gamma is I E p by I E and Alpha T is I C p by I E p. So, if you multiply 2. So, Alpha T times gamma is I C p by I E. So, this is gamma times I is actually I C p.

So, this I C n is actually I C p now is called reverse saturation current for the base collector junction.

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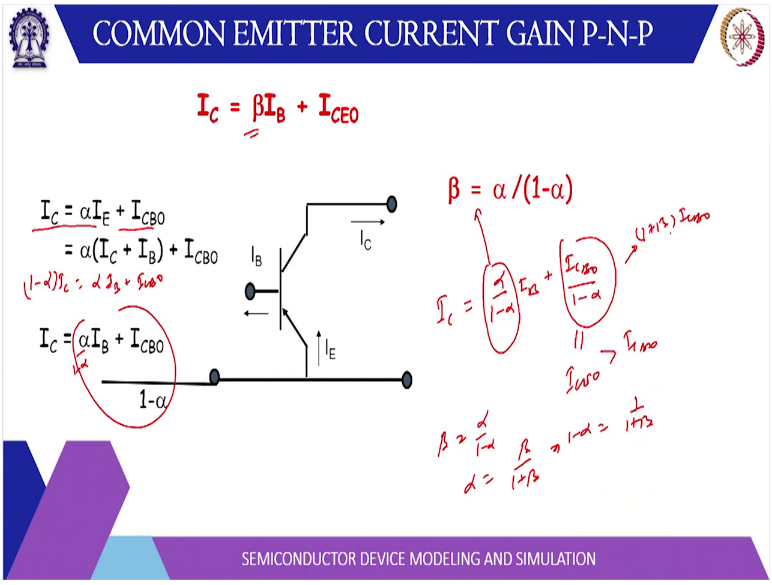

Now we can similarly write the equation for the common emitter. So, we can express I EC in terms of I B and that we can derive. We know that I C Alpha times I E + I C view that we have seen in previous slide and I can be written as I C + I B then when we take I C to this side. So, it becomes 1 minus Alpha times I C is equal to Alpha times I B + I C B O. So, what we do we divide by 1 minus Alpha.

So, it I C is Alpha by 1 minus Alpha times I B + I C o b 1 minus Alpha. So, this is actually displaced. So, let me write here I C is alpha y 1 minus Alpha times I B + I C B O by 1 minus Alpha. So, this Factor Alpha wave 1 minus Alpha is called beta and that we call common emitter current gain. And this I C by 11 is Alpha is called I C e o. So, this is a common emitter reverse saturation current for the collector junction and you notice I co is larger than I C bo because Alpha is less than one.

In fact you can find out that 1 minus Alpha from here beta is equal to Alpha by 1 minus Alpha. So, you can write here that Alpha is equal to beta by 1 + beta. So, this means 1 minus Alpha is equal to 1 by 1 + beta. So, 1 by 1 minus Alpha is 1 + beta times I C b o. So, that is equal to I C e o. So, this is a common emitter current gain.

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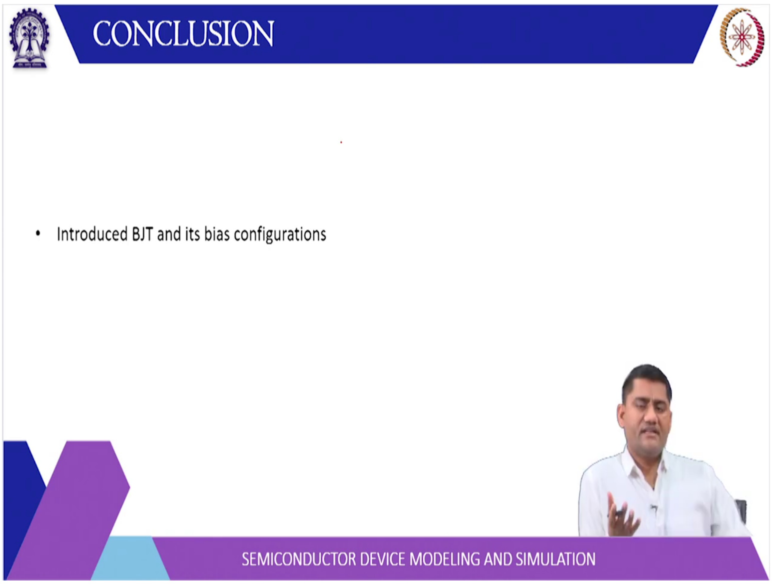

So, in this lecture we have discussed various BJT configurations and we have discussed the mechanism of the current flow in case of BJT and how do we achieve the transistor action. Next class we will drive the IV characteristic for the BJT using the micro carrier diffusion equation as we discussed in P-N junction diode and so on thank you very much. Hello welcome to the continuation lecture of on PN junction.

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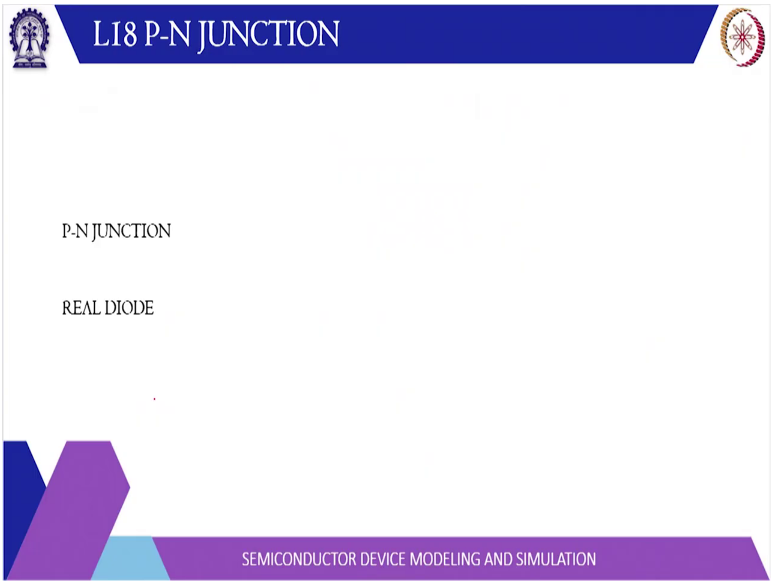

So, we have discussed about the PN junction we have discussed the electrostatic of the PN junction then we derived the current equation using solution to minority carrier diffusion equation then we developed this thing using charge conservation model.

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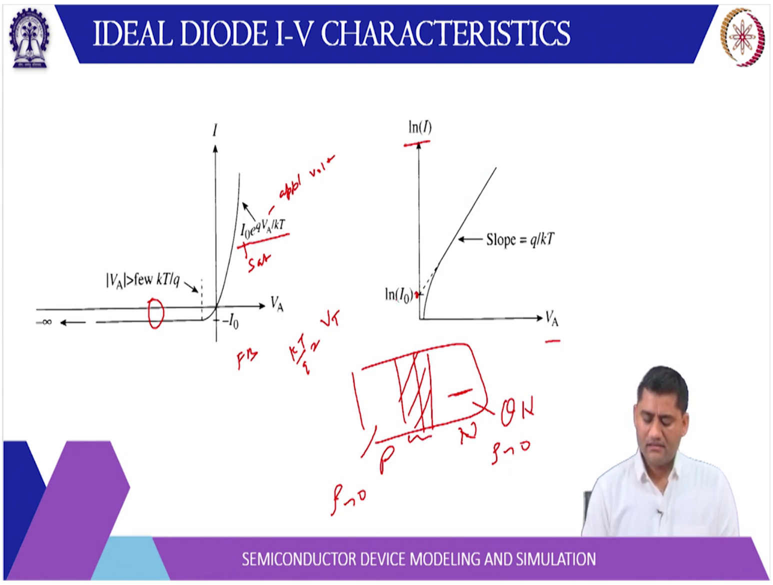

So, in summary we can write that for ideal diode current is given by some I naught times exponential q V by kT where I naught is the saturation current or reverse saturation current and v a is the applied voltage and T is the temperature k is a Boltzmann constant and q is the charge on electron and kT by q is **(()) (34:15)** called thermal voltage V T. And if you notice here in forward bias when the voltage is greater than zero or P tap is positive.

This current increase exponentially in the reverse bias there is a constant current and that basically you can go to any voltage in the reverse bias the current remains constant. Please recall that we derived this expression under the assumption that in the depletion region. So, this is your let us say P-N junction and this is a depletion region here in the depletion region there is no recombination or generation that was 1 major assumption.

Another assumption we assumed this as quasi neutral region. So, that means in this region charge was roughly zero and this side also the charge is roughly zero. So, all the charges in the depletion region only. Now we will consider what happens if we consider the realistic situation we can consider the generation recombination in the depletion region and we can also consider there may be some finite electric field in this region also.

So, in certain situation this effect becomes dominant then of course we have to include them and this right side curve is basically is a plot of logarithmic current along y axis and the applied voltage and this is basically a linear more or less linear year and if you extend this linear region why it intersect the y axis at log of I naught.

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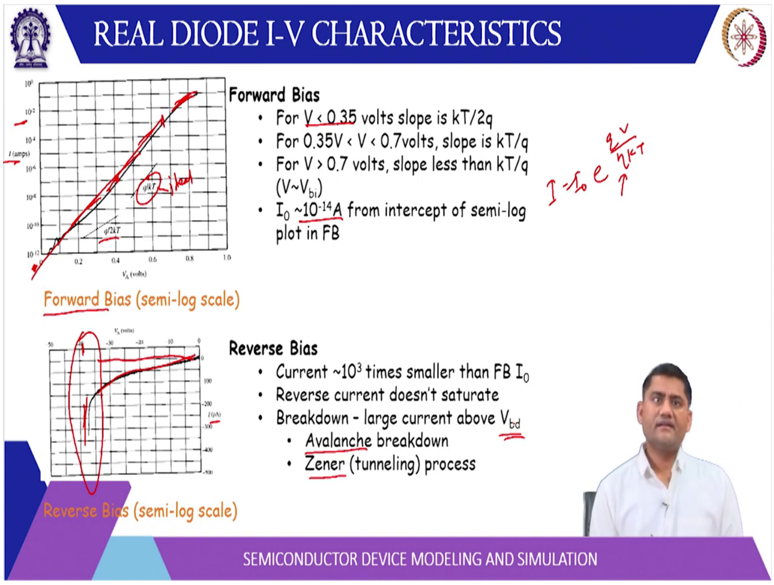

Now this is the; if you consult some data sheet for a typical diode you will get characteristic like this. So, this is forward bias. So, in forward bias in the region around 0.35 to 0.7 this slope is q by kT. So, that means here the diode is behaving like an ideal diode below this region the slope is less above this region also slope is reduced. So, this can be approximated by q by 2 kT.

So, for voltage less than 0.35 and greater than 0.7 of course it can be again not kT by q but some other slope. So, that is why for General diode equation we use I is equal to I naught exponential q v by eta kT where eta is a identity factor and it is a function of voltage and other condition. So, in different region you can use different data for different operating condition.

And the reverse saturation current is typically order of 10 raised to power minus 14 ampere that you can get from the intersection if you extend this linear region it will intersect somewhere here so, which is around tennis minus 14. In the reverse bias you notice we expected it to be a constant current but it is gradually increasing. And if you look carefully it scales as square root of the voltage and the current is fairly small if you see here is order of Pico ampere and this one is in if you see here around this region its order of few Milli ampere.

But 2 things you can notice in the reverse bias it is not constant and at certain voltage there is a sudden change. So, this slope becomes quite large this region we call a breakdown there are 2 main mechanisms that are responsible for the breakdown 1 is called Avalanche breakdown other is called a zener breakdown. So, and the voltage at which the sudden increase in the current appears that is called breakdown voltage.

So, reverse saturation current is not saturating rather it increases and at certain point or that certain voltage there is a large reverse current due to the breakdown.

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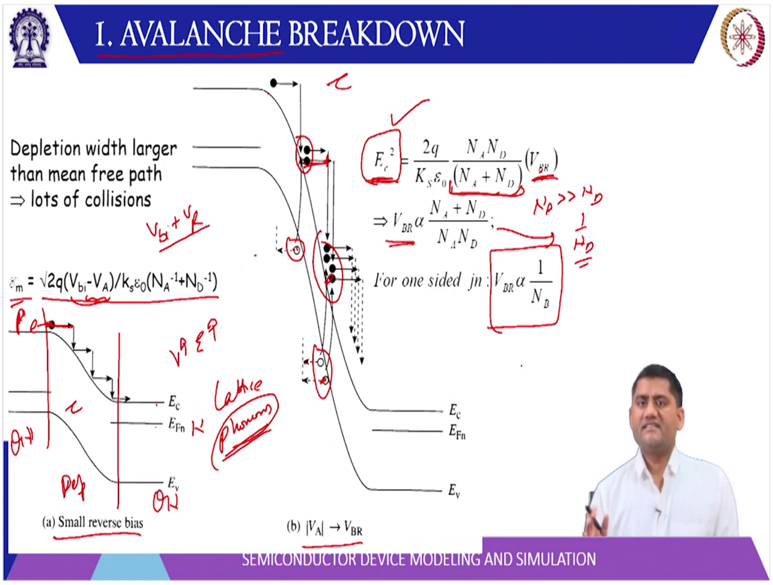

Now let us discuss one by one this figure is for small reverse bias. So, in small reverse bias what happens this is quasi neutral region this is also quasi neutral region and this is your depletion region. So, typically in the reverse bias this depletion width as you increase the reverse bias this depletion width will increase. So, it is long enough and in the depletion region carriers are also a small in number.

But as you increase the voltage what happens the electric field increases as you can see here electric field is given by square root of 2 q V bi minus V A. So, this is basically if reverse bias then it add up basically. So, you can say V bi + V R because we applied is for forward bias. So, in Reverse bias this is negative. So, you can say V bi + V R. So, it increases as a square root of voltage.

Now let us say electron moves from n type or P type because in reverse bias is the minority carrier that will go. So, this is n type this is p type because formula is close to the conduction band here then electron a minority carrier will move from here and it will get accelerated and it will move certain distance after which it will get scattered. So, the time is roughly fixed the time between 2 collisions is called scattering time. So, in that time it get accelerated by this field now in the small reverse bias the field is a small.

So, it gets an energy but it is not high enough to knock out another carrier from the valence band. So, what it does it transfers the energy to the lattice vibration or phonons. So, these electrons move around and they transfer their excess energy to phonons. So, that basically causes some kind of heat that is it. So, phonon is basically kind of heat or lattice vibration but at high electric field what happens the energy acquired by this electron is quite high.

So, you can see the right figure here when the reverse bias voltage is close to the breakdown voltage. So, this for the small distance there is a large change in the potential. So, their energy changes by quite a bit amount and that is comparable to the bend Gap. So, what will happen as it collides whenever another electron here the energy released can be taken by third electron and it can produce a electron and hole pair and that effect actually multiplies.

So, what happens this electron goes to right it produce electron hole pair then electron hole pair jet is generated then now 2 electron go and hole will move to the left then 4 electron will go to the right and 2 hole to the left. So, these all that are coming here these all that are coming here they will again generate another electron hole pair so that way when this multiplication is beyond certain critical value we have this Avalanche breakdown. So, the current actually increases very rapidly.

So, now what will limit the current the current will be limited by the circuit. So, circuit will have certain resistance. So, like in zener diode you see where the effect is zener not the Avalanche breakdown but these are used in photo detectors where very small number of photons are there. So, if you have to detect it then this APD called Avalanche photodiodes are used there. So, this breakdown voltage gives rise to this maximum electric field and we can say this maximum electric field.

We are critical electric field at which the energy acquired by the electron for a distance travelled of Tau the mean Collision time is enough or comparable to the bandgap. So, that it can knock out another electron that that is the critical electric field basically and if you compare it this is dependent on the this applied voltage and the doping level. So, for if you know the breakdown voltage then for a given breakdown voltage you can find out what is the corresponding doping.

So, if you change that open then the breakdown voltage will change because this critical electric field is fixed basically. So, you can say that because critical electric field is fixed. So, this product has to be constant. So, that means your back down voltage proportional to N A + N A N A + N D by N A N D and if it is let us say 1 sided junction let us say n a is much larger than N D. So, then this expression will simplify to 1 by N D.

So, the lower doped side basically. So, if n d is more than much larger than any then this will be 1 by N A. So, this is basically for 1 sided junction breakdown voltage is 1 over the doping consultation of lower doped side and you can understand this way also the lower down side the depletion region will extend maximum on the lower doped side. So, there all this multiplication will take place.

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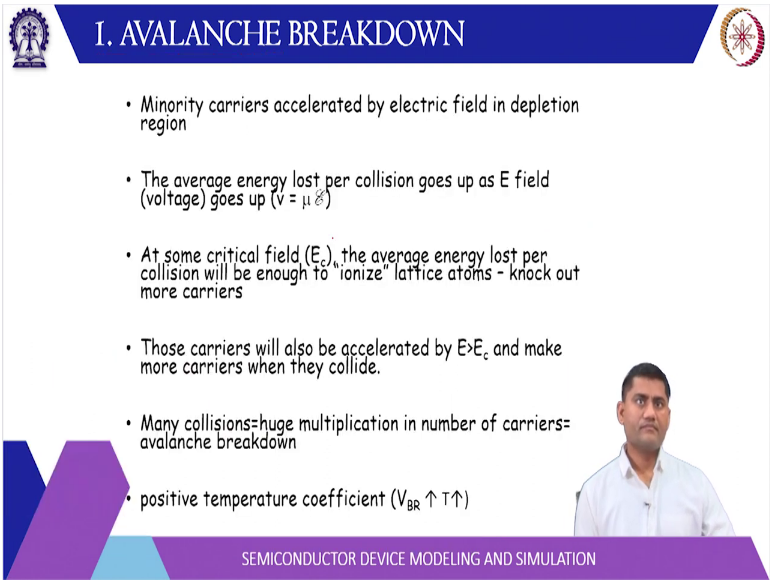

Now these minority carriers are accelerated on the electric field. So, this we have already discussed and at high field of course this V equal to Mu it does not apply but in the linear region up to certain point this is true that V is equal to Mu A and then of course when there is a critical electric field the average energy lost is in enough to ionize the lattice atoms or knock out the electron.

So, when the applied voltage is such that the electric field in the depletion region goes to beyond critical electric field. Then this evidence breakdown take place another thing is important here this Avalanche breakdown is positive temperature coefficient. Now why does it apply positive temperature coefficient not 11 let us say you increase the temperature then if you increase the temperature then the random thermal motion or the thermal velocity will increase.

If thermal velocity is more; then the time between 2 collisions will be less. So, now for a given electric field if the tau is reduced then the energy acquired will be less because now it is accelerated with that electric field for a smaller time. So, let us say for let us say T 1 the critical reactive field was E 1 E C1 if T 2 is more than T 1 then and I say this is Tau one. So, now Tau 2 will be less than Tau 1 for a greater temperature but it is a combination of these 2 that decides that electron will get sufficient energy to ionize.

So, if temperature this tau is reduced then your E C2 has to be more than E C1. So, that they get sufficient energy within a smaller time. So, that means your breakdown voltage will increase. So, as the temperature increases the breakdown voltage increases and that is a characteristic of avalanche breakdown.

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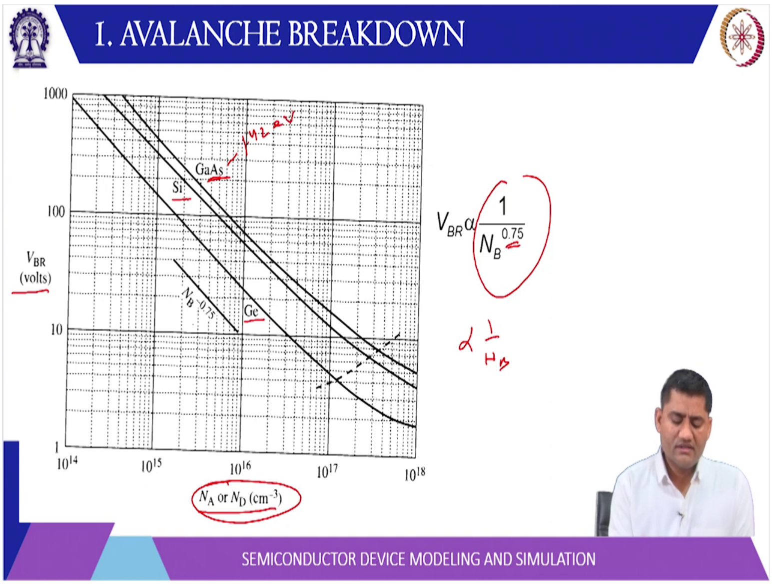

And this is the curve which relates the breakdown voltage versus the doping in case of these materials gallium arsenide, silicon and germanium. And as we derive that it is roughly proportional to 1 over NV and if you fit it with the experimental value you get around power 0.75 and with the increasing doping the breakdown voltage is actually reducing now this doping is on the lighter doped side.

So, this is our one sided junction. So, and you can also see the breakdown voltage for gallium arsenide is more than silicon that can be explained as the bandgap for gallium arsenide is 1.42 electron volt for silicon is around 1.12 electron volt germanium is even smaller so, around point six seven electron volt. So, because the bend Gap is less so, the breakdown voltage is also less because now energy required is smaller compared to gallium arsenide in Silicon and compared to Silicon less energy required in germanium.

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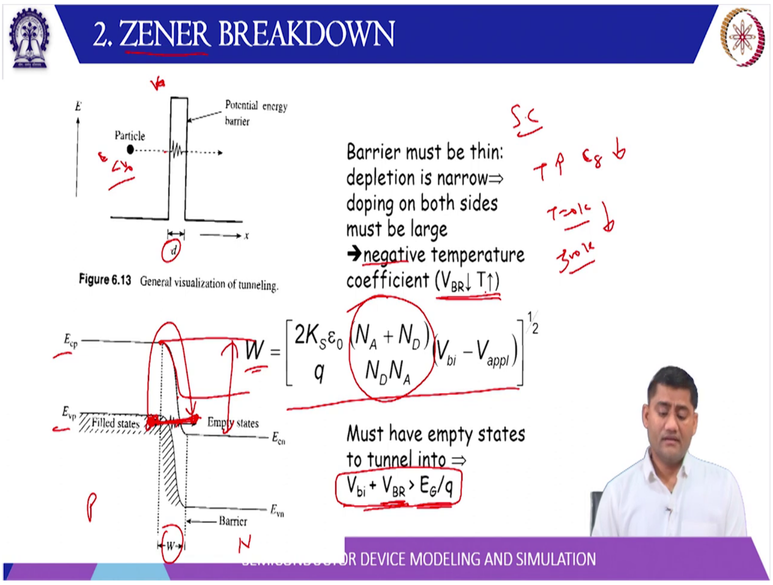

Now the second mechanism is the zener breakdown. In case of zener breakdown the mechanism is the tunnelling. So, if you look at this picture here let us say this is some potential barrier with height V naught and the barrier thickness is d. So, this particle if thickness is small comparable to the De Broglie wavelength of this particle there is a finite probability that this electron can go over this barrier even though its energy e is less than V naught the energy of the barrier.

So, in case of P-N junction diode let us say this is your band diagram. So, this is the balance band conductor vent on let us say p side and this is the conduction balance band on the N side and this is a depletion width now there are electrons here because in P side this is this has some electrons here some failed state some empty states or some field electrons are here in case of this side there will be some electron some empty state.

So, these electrons from the balance vent they have the same energy as the electrons on this side. So, this electron can easily go here the only thing is that it has to cross over this barrier but if this thickness is sufficiently small then there is a finite probability for this electron wave to exist on other side also. So, if the depletion width is small that expression we have valid drive if the depletion width is small.

Then there is possibility that this electron can tunnel through this barrier and the mechanism responsible for this breakdown is the tunnelling and we call this as zener breakdown. So, large number of electrons are here because this is field band and they can cross over. So, the relation is basically given like this that the V bi + V br. So, V bi is the built-in potential V is the replied reverse bias. So, these 2 voltages are larger than the bend Gap energy.

So, this basically this is this is the V bi + V br this is larger than the bandgap energy because if it is smaller than Banda cap energy then it will not go up to here it will remain somewhere here now this electron can tunnel through because tunnelling requirement is that initial energy and final energy there should be same and of course this width will be small if this doping is large because it is universally proportional to the doping.

So, for high doping on both sides we can accept expect a zener breakdown mechanism. And another thing you can notice here compared to Avalanche breakdown here the the temperature coefficient is negative that is as the temperature increases the breakdown voltage decreases that is contrary to the Avalanche breakdown. Now what happens here in case of semiconductor as the temperature increases the bandgap actually decreases.

We can take you can recall the discussion regarding the band structure where we sort that at low temperature zero Kelvin there was some bandgap at 300 Kelvin the bandgap was reduced and as you increase the temperature the bandgap reduces. So, as if you increase the temperature bandgap has reduced now if you look at this relationship if bandgap is reduced the V br requirement is also relaxed.

So, you will require a smaller voltage for a breakdown. So, as temperature increases the breakdown voltage decreases. So, this is also used to find out whether the breakdown mechanism is Avalanche breakdown or zener breakdown you can find from the temperature coefficient.

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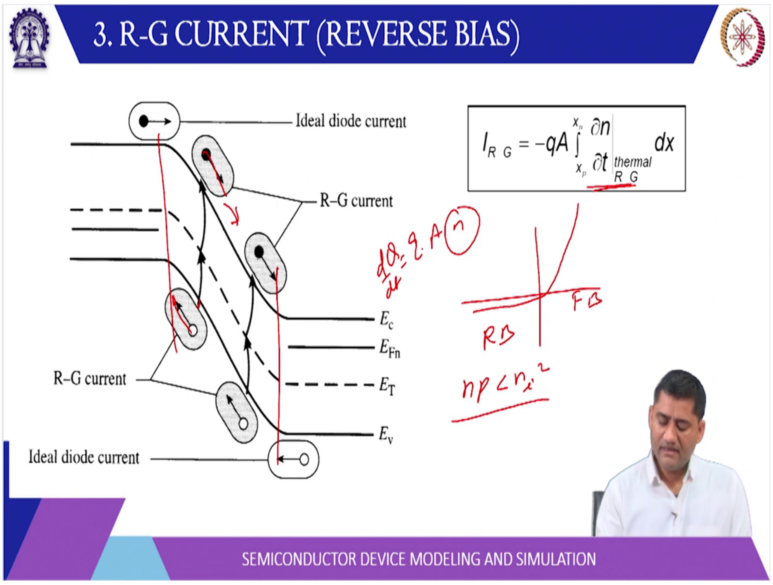

Now let us look at the IV curve of a P-N junction diode. So, you can recall here the IV curve basically look like this, this for ideal diode. So, in forward bias exponential in reverse bias it is a constant and that was the case when we ignore the generation recombination in the generation recombination in the depletion region now in real diode there is a certain amount of generation recombination in the depletion region.

So, you can see this is a depletion region. So, depletion means number of carries less. So, that means the mechanism that will be there will be generation because here np product will be less than n i Square so, there will net generation in this region. So, when the electron volt pair is generated then that will flow according to the field. So, if electrons are generated then electron will flow down L if all is generated it will go up like this.

So, some current will flow due to the generation recombination and we can estimate that current by simple expression number of carriers times q times the area of cross section times the number of carriers. So, number of carries is proportional to the the generation rate of these electrons. So, this is total q and dq by dt will be d by dt of this. So, q and A are constant. So, you can write dn by dt. So, this dn by dt is a thermal generation rate.

So, and of course electron is a charge minus q. So, you can write minus q times dn by dt and you integrate over the width of the depletion region this is 2 integrate of the width of the depletion region and if we assume that the rate is constant that we can find out for the for entire Adventure semiconductors.

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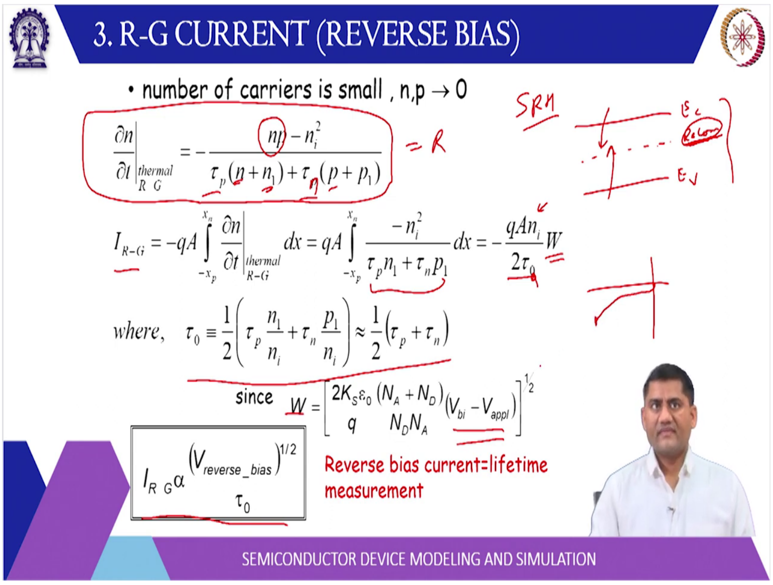

We have this SRH recombination Sock Layer Read all mechanism. So, where the the net recombination rate this is a net recombination rate is n p minus n i Square divided by Tau p times n + n 1 + Tau this should be Tau n i think Tau n times p + p 1 where n p is the carrier consultation electron concentration whole consultation ni is the intrinsic carrier concentration that is fixed at a given temperature and the Tau p are basically carry a lifetime for Tau p and Tau n k l item for electron and all and n 1 p 1 are some constant basically computed constants.

So, in the depletion region np product is small. So, you can ignore it compared to n i Square. So, you can just write numerator will become n i square divided by Tau V times and N is PG small. So, you can write this n 1 p 1 there in the denominator and this can be represented by some constant Tau node let us say. So, you can write that this generation current is minus q a n i by 2 Tau times w, w is a depletion width and n i is the intrinsic carrier concentration and tau is rated to the carrier lifetime.

So, and these are different situations where these approximation can be applied. So, it is kind of average if this of course we will discuss later on when we discuss the semiconductor describing equations we will drive this expression right now you can understand like this let us say this is your semiconductor this is the balance band this is the conduction band. So, apart from doping level there are certain deep impurity levels and they are somewhere close to the middle of the bandgap and these impurity level act as a recombination centers.

So, they will capture electron they will capture a hole and they can combine here because now these electron will have to cross the half of the bandgap energy barrier. So, there they can easily recombine if there were no this recombination center then the energy required will be equal to the bandgap. So, this recombination set centers actually ease out the process of recombination.

So, they increase the recombination rate and the recombination rate actually depends on where these recombination centers are located. So, this n 1 factor depends on the position of this recombination center. So, with this by the detail model we can calculate these constants also. So, right now let us use this expression this is the expression for net recombination rate and we know that width is proportional to the square root of applied voltage.

So, you can see this generation recombination current in case of reverse bias the generation current is proportional to w by Tau and w is proportional to the square root of by s voltage. So, you see this is proportional to the square root of reverse bias voltage divided by Tau naught. So, that is why in the reverse bias we saw that current was increasing like this. So, up to this region before breakdown it is the generation current that is responsible for this kind of characteristic in the PN junction diode.

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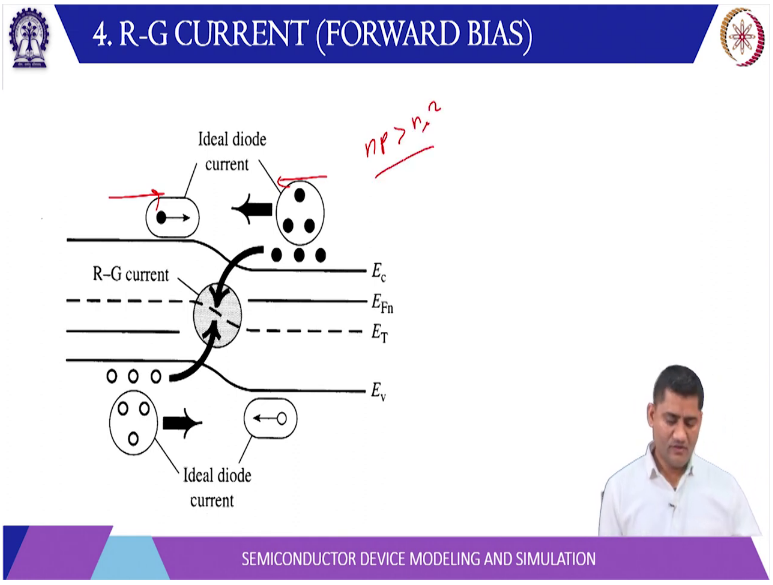

Then in case of forward bias there is a large number of carriers that are injected from both sides. So, now np product is more than n i square. So, there will be net recombination if you look at this expression np product is more than n i Square. So, there will be net recombination.

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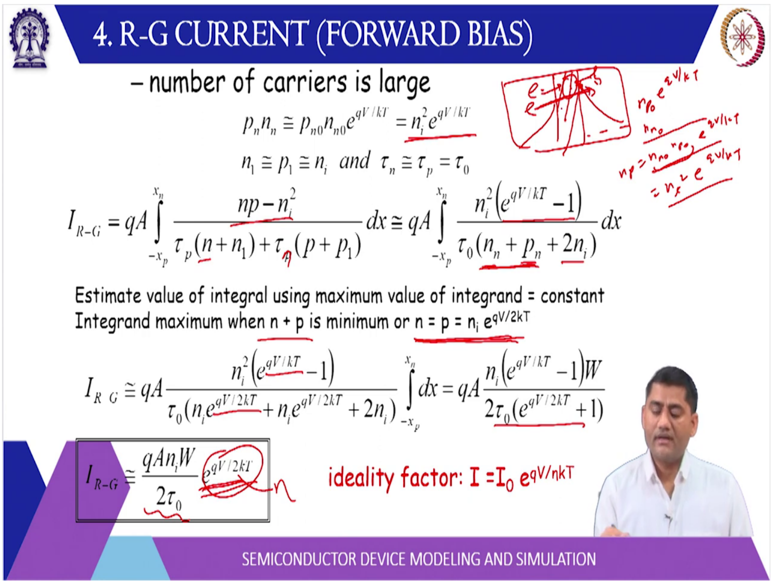

So, we know that np product is if you recall this PN junction this is a magnetically diffusion equation. So, here it was let us say this is n p naught exponential q b by kT that was maximum n right and and N naught remains M. So, if you multiply these 2 what you get you get n n naught n p naught so, np product s exponential q v by kT. So, this is a product. So, this is n i Square n p naught n naught. So, this is n i Square Times exponential q V by kT.

So, this is what written here that P-N product is n is for exponential q b by kT and that we can substitute in this expression for the recombination current. So, the numerator becomes n i Square exponential q V k q V by kT minus 1 a denominator again as n and Tau p and Tau n. So, this can be replaced by Tau n times n n + p n + 2 n i and because n n p n is quite large you can ignore 2 n i R. So, this can be done n i exponential q V by 2 kT because this is n n p n is the electron concentration inside electron concentration on P side.

So, if np product is this and then you can write n piece if they are equal. So, that is basically some kind of high level injection is taking place ah. So, for high level or when this is maximum you can write n p is equal to they are equal and this is n i exponential q b by 2 getting. So, basically square root of this thing then if you substitute in the denominator. So, numerator has exponential q b by kT and denominator is exponential q V by 2 kT.

So, if you take the ratio of these 2 you will get exponential q b by 2 kT and then some pre factors q A and I W by 2 Tau naught the W is of course proportional to V bi minus V applied. So, that change in the applied voltage in the forward bias is very small. So, that will not play much at all. So, this will be the basically the controlling term exponential q V by t k t. So, here 2 is identity Factor and that is applicable for smaller bias 0.35 to 0.7 and at higher bias also other Factor will also come into the picture.

So, when large number of carries are flowing into other side and there is a net recombination in this region. So, you can visualize picture like this electrons come from here whole come from here. So, this electron will do not go but they recombine here and they disappear. So, number of electron moving is much larger than. So, total current is electron crossing over plus electron recombining or hole crossing over plus whole recombining that is a total current. So, this is the case that happens between the 0.35 to 0.7 volt.

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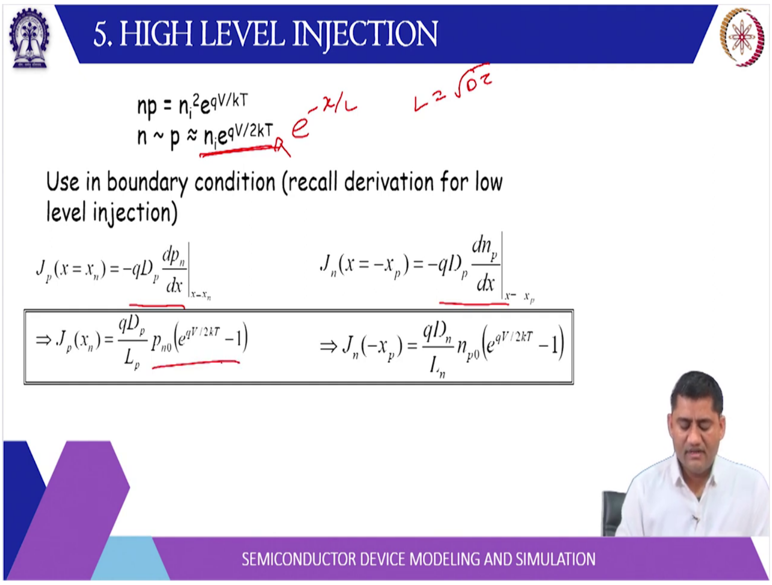

Then at high level injection of course you can directly write this same thing np product is n i Square exponential q V by kT and you can substitute this equation for the minute carrier diffusion in the Quasi neutral regions and then of course when you calculate the diffusion current q dp times dp by dx for n site because holes are minority there and for electrons on P side you can write q dp times dn by dx.

And this is the expression for n and p and they are dependent or x is something like E to the power minus x by L where L is root of d Tau. So, so this will be basically q dp by L times p naught exponential q V by 2 kT. So, at high level injection also you follow this kind of characteristic exponential q V by 2 kT. So, this is valid for 0.35 to 0.7 and then sorry 0 to 0.35 and beyond 0.7. So, both cases you have this kind of characteristic one1 is due to high level injection another is due to recombination.

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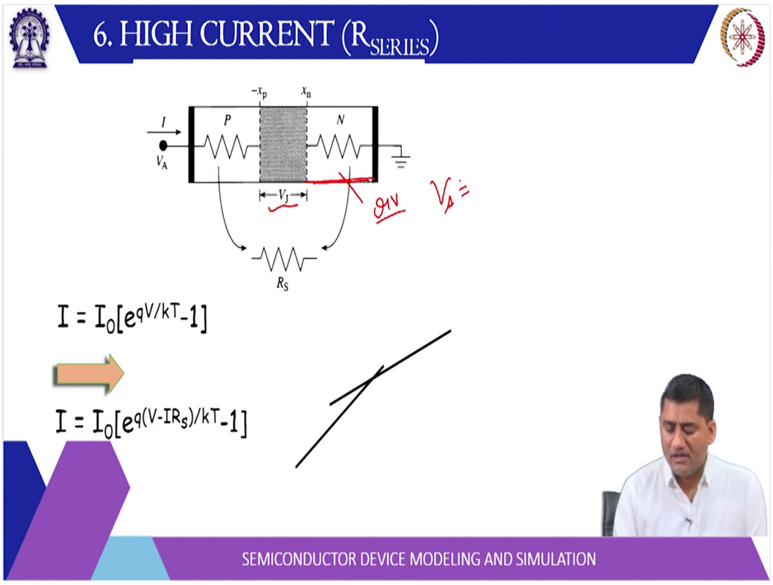

Now at even higher current this quasi neutral region approximation does not is not valid here. So, there will is there will be a finite drop in this region because there is large amount of current is flowing. So, although the resistance is small here but due to large amount of current there is some finite voltage drop. So, as we assumed that all the voltage drop appears across the junction that is not true. So, now V A is not equal to V J.

So, VA is applied voltage V J's are junction voltage or across a depletion region there is some finite drop in this region also and that drop will be V A minus V J or you can say it is also I times R s the regions the resistance of these 2 regions causing neutral regions. So, now your expression is I is equal to I naught exponential q V across the junction. So, that is V minus i R s by kT minus 1.

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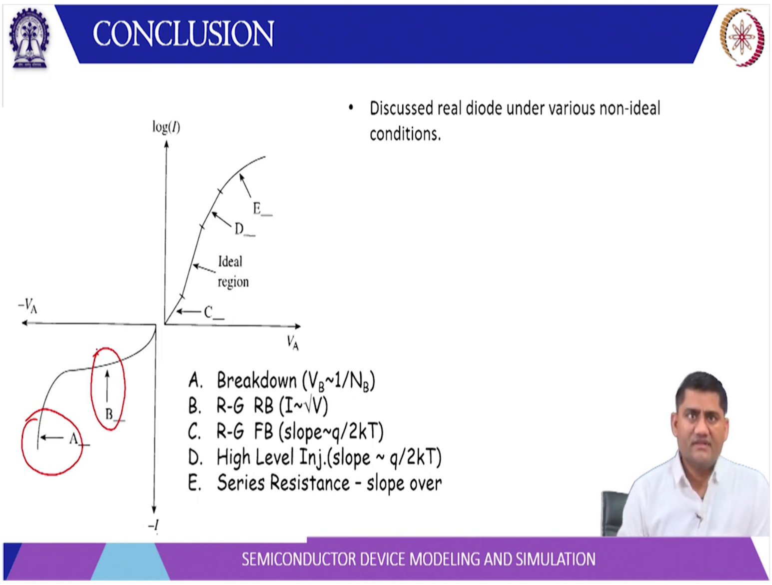

So, in summary we can say the IV curve of P-N junction consists of several regions where a is the breakdown region the mechanism can be Avalanche breakdown which has positive temperature coefficient it can be gener back down which has negative temperature coefficient then there is a recombination region the current due to the sorry generation this is due to generation. So, current due to the generation of the carriers in the depletion region because they are less number of carries in the depletion region at forward wise there is a injection.

So, this region is basically due to the recombination and the slope is q by 2 kT. Then of course this is the ideal region then beyond ideal reason again due to high level injection and then due to the series resistance there is some slope change. So, we have discussed the real diode under various non ideal conditions thank you very much.