Semiconductor Device Modelling and Simulation
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Lecture - 18
P-N Junction (Contd.,)

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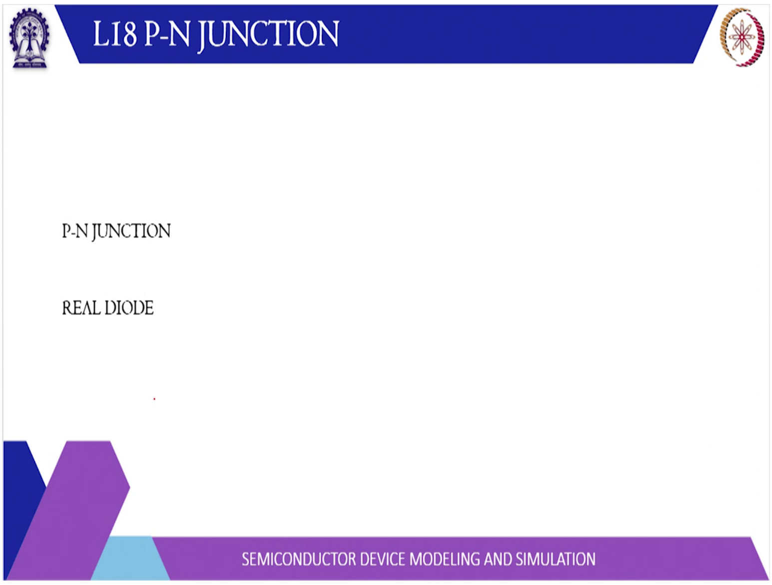

Hello, welcome to the continuation lecture of on PN Junction. So, we have discussed about the PN Junction we have discussed the electrostatic of the PN Junction then we drive the current equation using solution to minority carrier diffusion equation then we develop this thing using charge conservation model.

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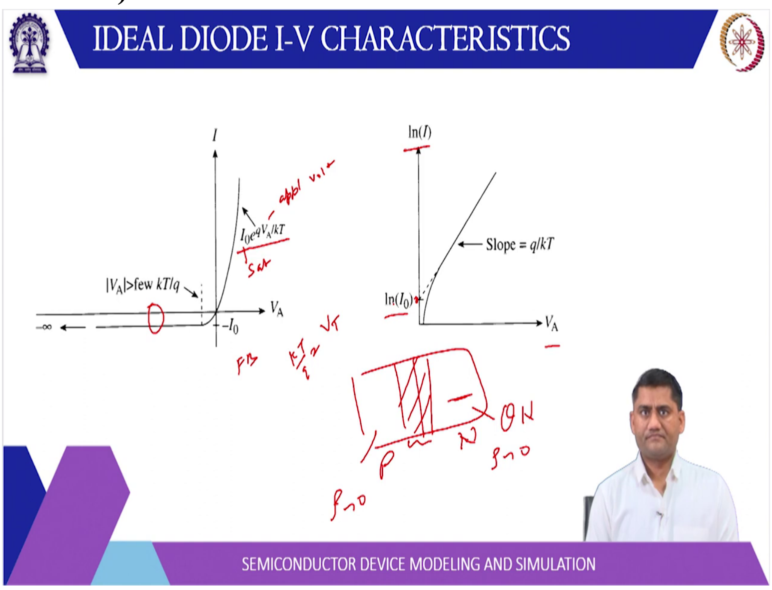

So, in summary we can write that for ideal diode current is given by some I naught times exponential q V by kT where I naught is the saturation current or reverse saturation current and V is the applied voltage and T is the temperature k is a Boltzman constant and q is the charge on electron and kT by q is non wire another name called thermal voltage V T. And if you notice here in forward bias when the voltage is greater than zero or P type is positive this current increases exponentially.

In the reverse bias there is a constant current at that basically you can go to any voltage in the reverse bias the current remains constant. Please recall that we drive this expression under the assumption that in the depletion region. So, this is your let us say PN Junction and this is a depletion region here in the depletion region there is no recombination or generation that was one major assumption.

Another assumption was 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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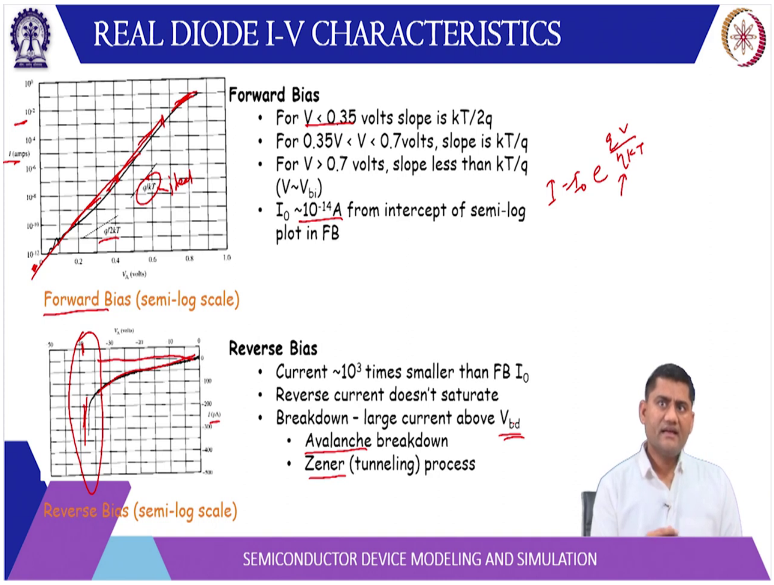

Now this is the if you consult some data sheet for a typical diode you will get characteristic like this. So, this is forward bias. So, in forward bias in the region around 0.35 to 0.7 this slope is q by kT. So, that means here the diode is behaving like a ideal diode below this region the slope is less 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 10 is to 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 you see here around this region this 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 certain change.

So, this slope becomes quite large this region we call a breakdown and there are 2 main mechanisms that are responsible for the breakdown one is called Avalanche breakdown other is called a zenar 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 at certain voltage there is a large reverse current due to the breakdown.

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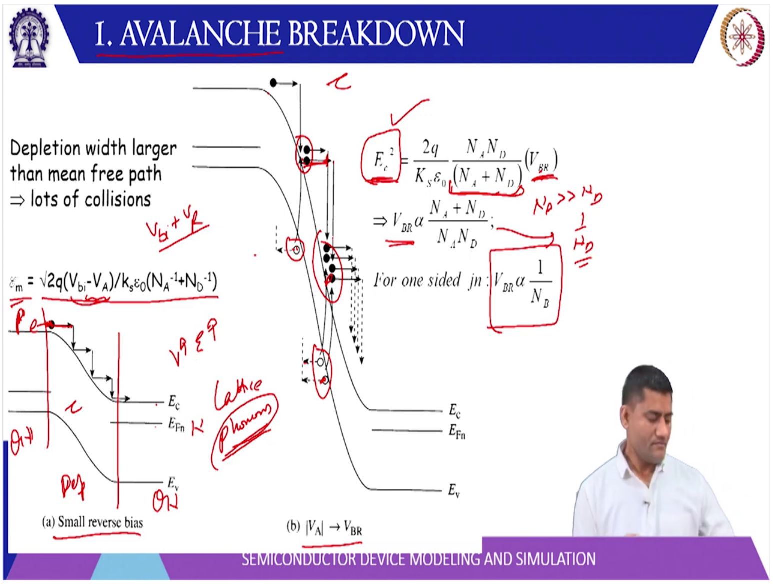

Now let us discuss one by one this figure is for a small reverse bias. So, in small reverse bias what happens this is quasi neutral region this is also quasi neutral region and this is your depletion region. So, typically in the reverse bias this depletion width as you increase the reverse bias this 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 the reverse bias is the minority carrier that will go. So, this is N type this is p type those 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 bandgap.

So, what will happen as it collides when 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, so what happens this electron goes to right it produce electron volt pair then electron hole pair Z is generated then now 2 electrons go and all will move to the left then four electron will go to the right and 2 whole 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 general 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 give 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 breakdown voltage is proportional to N A + N A N A + N D by N A N D and if it is let us say one sided Junction let us say n a is much larger than N D.

So, then this expression will simplify to one by N D. So, the lower doped side basically. So, if N D is more than much larger than any then this will be one by N A. So, this is basically for one sided Junction breakdown voltage is one over the doping consultation of lower doped side and you can understand this way also the lower dope side the depletion region will extend maximum on the lower doped side. So, there all this multiplication will take place.

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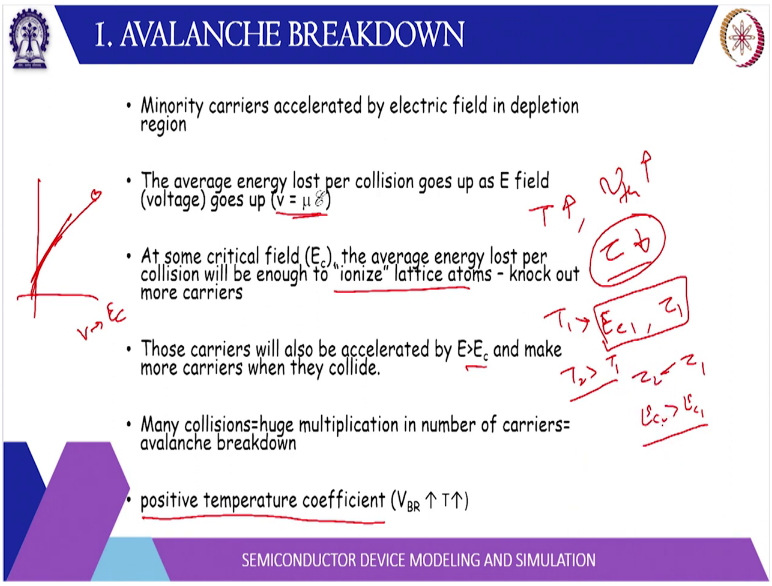

Now these magnetic areas are accelerated or the electric field. So, this we have already discussed and at high field of course this V equal to Mu it does not apply but in the linear region up to certain point this is true that V is equal to Mu a and then of course when there is a critical electric field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

So, 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 will 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 echoed 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 one the critical reactive field was e one e c one if T 2 is more than t one then and let us say this is Tau one.

So, now Tau 2 will be less than Tau one 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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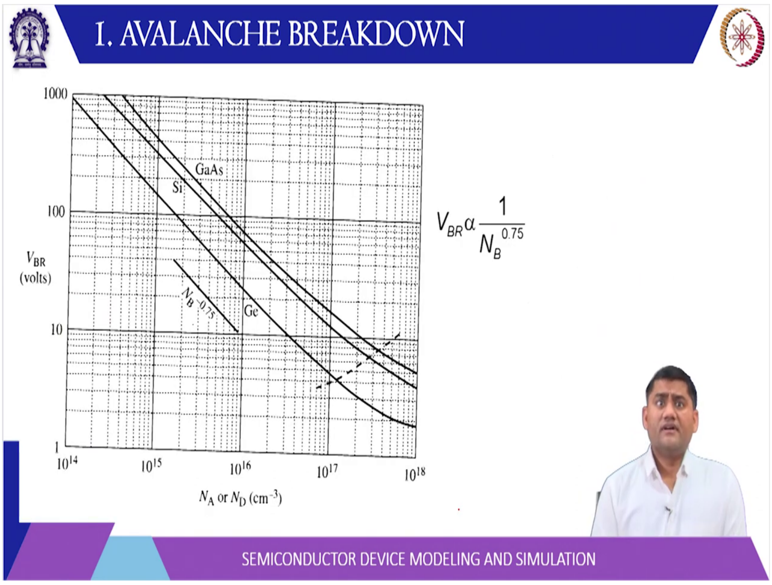

And this is the curve which relates the breakdown voltage versus the doping in case of these materials gallium arsenide silicon and germanium and as we derived that it is roughly proportional to one over N V and if you fit it with the experimental value you get around power 0.75 and with the increasing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

So, this is our one sided Junction ok. So, and you can also see the breakdown voltage for gallium Arsenal is more than silicon that can be explained as the band gap for gallimimation is 1.42 electron volt for silicon is around 1.12 electron volt germanium is even smaller. So, around 0.57 electron volt so because the bandgap is less. So, the breakdown voltage is also less because now energy required is smaller compared to gallium arsenite in Silicon and compared to Silicon less energy required in germanium.

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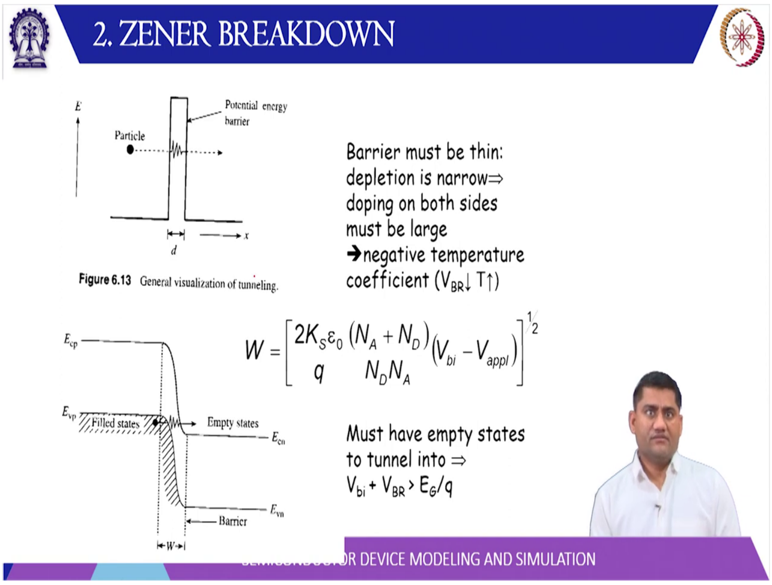

Now the second mechanism is the zener breakdown in case of zener breakdown the mechanism is the tunnelling. So, if you look at this picture here let us say this is some potential barrier with height V naught and the barrier thickness is d. So, this particle if thickness is small comparable to the De 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 PN 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 weights now there are electrons here because in P side this is this has some electrons here some failed State some empty state. So, some field electrons are here in case of this site 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 already derived if the depletion width is small.

Then there is a 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 vent and they can cross over. So, the 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 bandgap energy.

So, this basically this is the vvi bbr this is larger than the bandgap energy because if it is smaller than pentagram 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 side we can accept expect a zener breakdown mechanism and another thing you can notice here compared to average breakdown here the the temperature coefficient is negative that means 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 require you can recall the discussion regarding the band structure where we showed 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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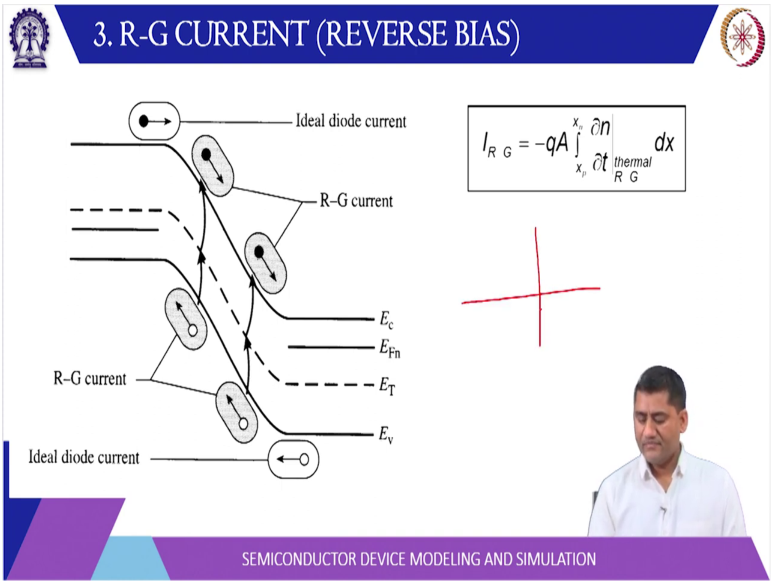

Now let us look at the IV curve of a p n Junction diode. So, you can recall here the IV curve basically look like this for ideal diode. So, in forward bias exponential in reverse bias it is a constant and that was the case when we ignore the generation recombination in the generation recombination in 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 carrier is less. So, that means the mechanism that will be there will be generation because here N P 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 a foul 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 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 D n by D it 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 integrator of the width of the depletion region and if we assume that the rate is constant that we can find out for the for indirect band semiconductors.

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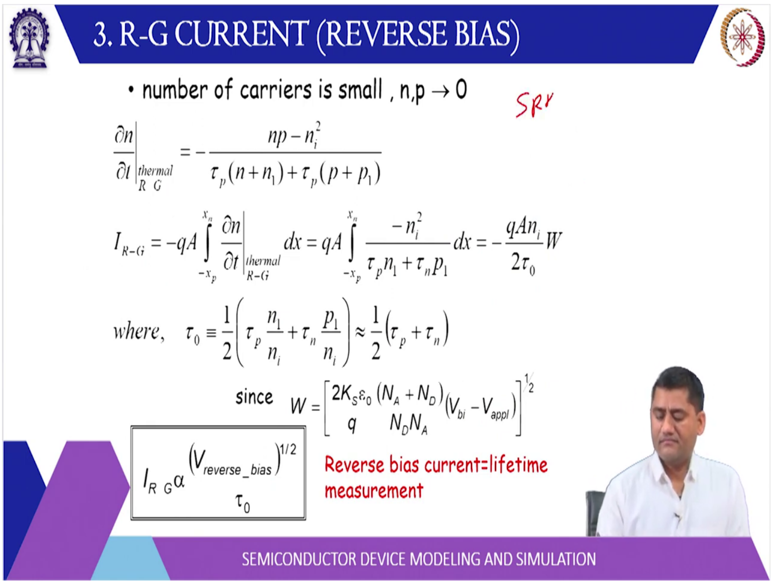

We have this SRH recombination sock layer read all mechanism. So, where the net recombination rate this is a net recombination rate is np minus N i Square divided by Tau p times n + n 1 + Tau this should be Tau n i think Tau n times p + p 1 where n p is the carrier consultation electron concentration whole consultation n i 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 and carry light term 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 PC 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 is a depletion width and n i is the 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 this recombination centers are located. So, this n 1 factor depends on the position of this recombination center. So, with this whether 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 y 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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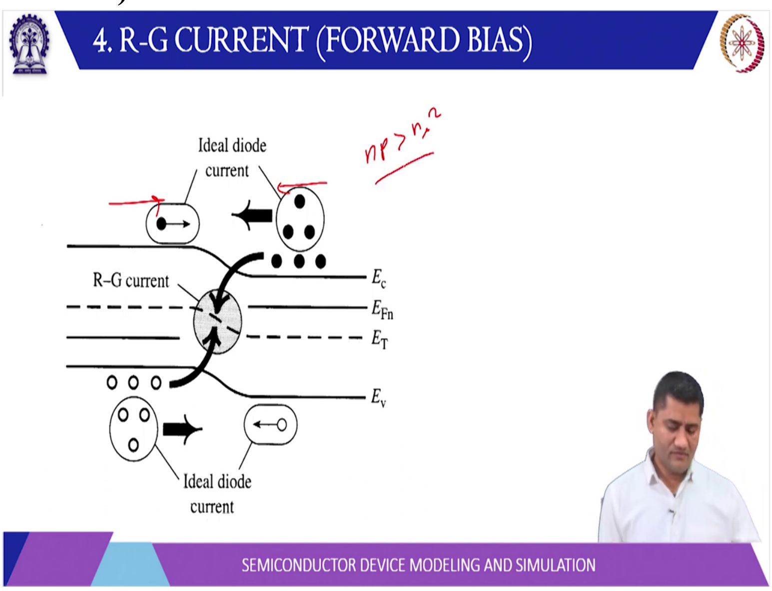

Then in case of forward bias there is a large number of carriers that are injected from both sides. So, now NP product is more than n i square. So, there will be net recombination if you look at this expression NP product is more than n i Square. So, there will be net recombination.

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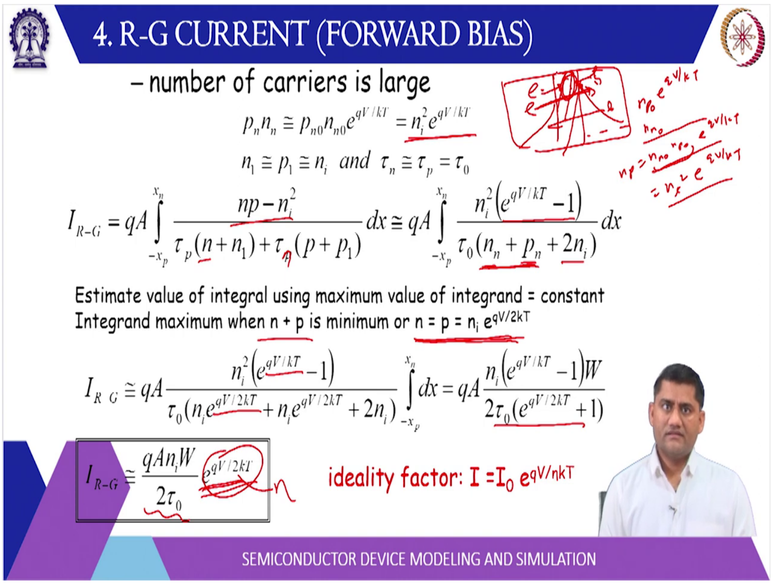

So, we know that NP product is if you recall this PN Junction this is a minority carry diffusion equation. So, here it was let us say this is NP naught exponential q b by kT that was maximum n right and n n naught remains same. So, if you multiply these 2 what you get you get n n naught n p naught. So, n p product is exponential q V by k T. 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 k t. 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 cubic q b by kT minus one a denominator again is 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 here.

So, this can return n i exponential q b by 2 kT because this is n and 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 V by 2 getting.

So, basically square root of this thing then if you substitute in a denominator. So, numerator as exponential q b by kT and denominator is exponential q b 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 kT. 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, the last 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 + electron recombining or hole crossing over + 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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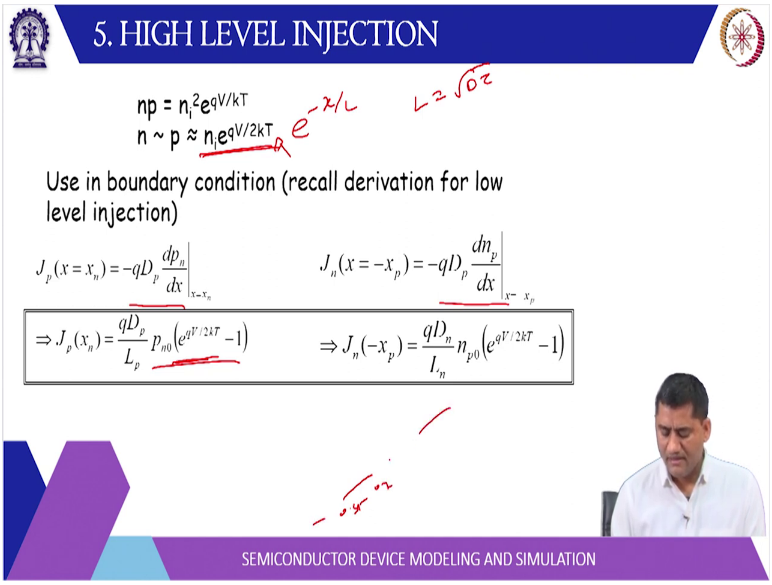

Then at high level injection of course you can directly write this same thing NP product is n i square exponential q V by kT. And you can substitute this equation for the meiotic carrier diffusion in the Quasi neutral regions and then of course when you calculate the diffusion current q D p times dp by dx for n site because holes are minority there and for electrons on P side you can add q D p times dn by dx and this is the expression for N and P and they are dependent on x is something like e to the power minus x by L where L is root of D Tau.

So, this will be basically q d p by L times p a 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 0.7n and then 0 to 0.35 and beyond 0.7. So, both cases you have this kind of characteristic one is due to high level injection another is due to recombination.

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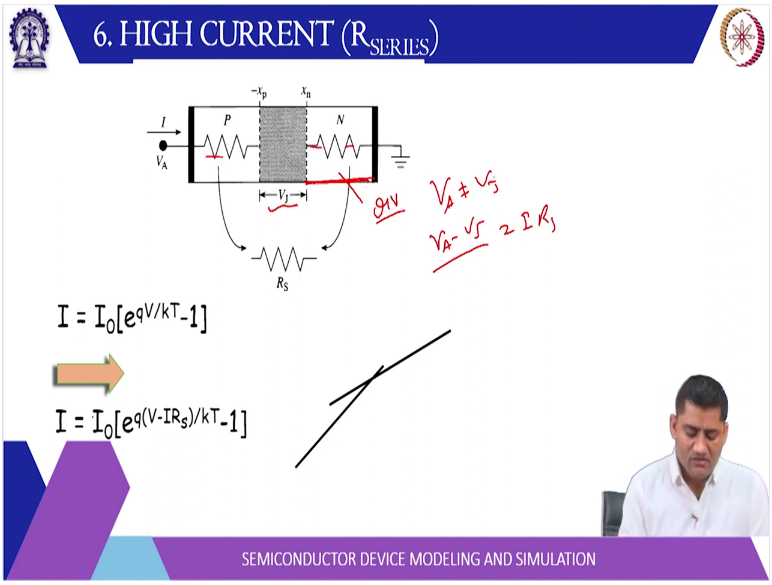

Now at even higher current this quasi neutral region approximation does not is not valid here. So, there will is there will be a finite drop in this region because there is large amount of current is Flowing. So, although the resistance is small here but due to large amount of current there is some finite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

So, V is applied voltage V j is a 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. So, or you can say it is also I times r s the reason 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 one.

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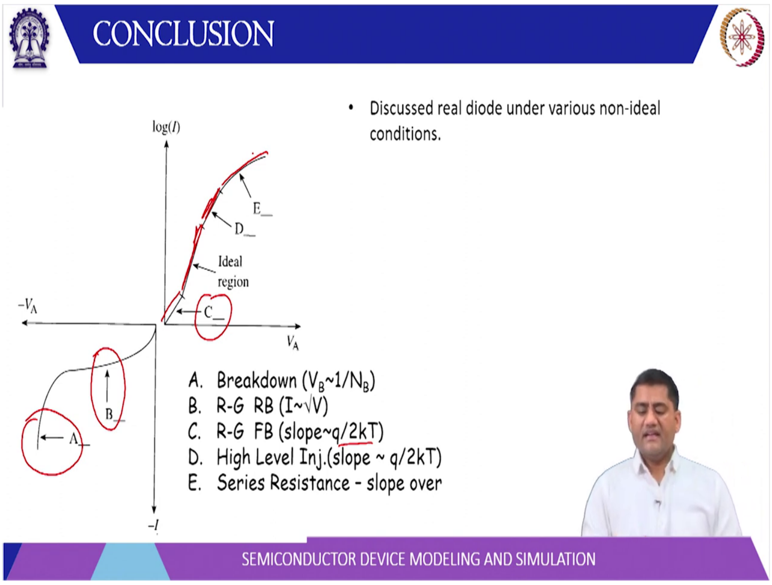

So, in summary we can say the IV curve of PN Junction consists of several regions where A is the breakdown region. The mechanism can be Avalanche breakdown which has positive temperature coefficient it can be zener breakdown which has negative temperature coefficient then there is a recombination region 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.