Fundamentals of Semiconductor Devices
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Lecture – 18
p-n junction under bias (contd.)

So welcome back, so what did you learn in the last class? We learnt about the forward bias and reverse bias p-n junction what is the basic definition, how the depletion with and the built in potential change with bias and we started to understand in details about forward bias p-n junction. I told you that when you apply a forward bias electrons from the n side and holes from the p side and now injected to the opposite sides and so the barrier reduces the depletion width also shrinks and because there injected.

So, holes are injected to the n side they become minority they decay. So, that decay has a profile. Similarly electrons are injected from n side to p side, they will decay in the p side that decay will again have a profile this profile is exponential decay if it is a long diode that is what we are considering here and because the carriers are decaying the derivative also will be exponentially decaying. So, the current which is the derivative the diffusion current of holes and electrons in the respective sides will also decay.

That is what we have learnt, we are established the mathematical expressions for those decay and we also told you how the carrier profile decays. And, now I asked you a question the total current in the diode or the device has to be same has to be constant throughout. So, the diffusion currents are decaying the something else there is compensating such that the total current is constant, so that is what we will start from today ok. So, we will come through a whiteboard we look at the last slide that we had discussed.

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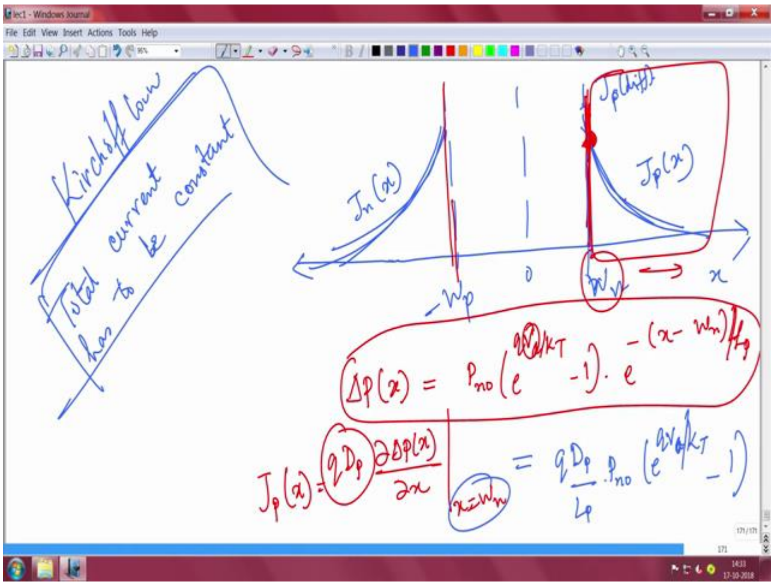

So, the hole current and the electron diffusion current will decay on the other side, if you recall the so I will talk about say only the n side how the holes are decaying because, the same thing can be applied to the p side. So, I told you the excess holes on this side will decay as p_{n0} which is n_i^2/ N_d $(e^{qVa/kT}$ -1) $.e^{(-x-Wn)/Lp}$ that is the applied voltage V a is the applied voltage the holes will diffuse.

And if I take a derivative of this now qD_p Δ p(x)/dx this will give you the hole current the diffusion current because of hole is a function of x. I do not want to I mean you can do the mathematics but of course, I want to find out this particular value that x = W_n which means what is the diffusion current at this point, at x=W_n at this point what is the diffusion current here.

It will decay of course, but I want to know the diffusion current at this point at the edge this is the edge of the depletion region; this is the edge of the depletion region, so at the edge of the depletion region what is the value. So, if you take a derivative of this multiplied by qD_p and you put x equal to W_n then you will get this value and that value turns out to be qD_p/Lp* p_{n0} which is the minority carrier hole concentration which is the base line into what; $e^{(qVa)}$ that is the applied voltage V_a/kT -1; there is no dependent on x because x equal to W_n at this point right.

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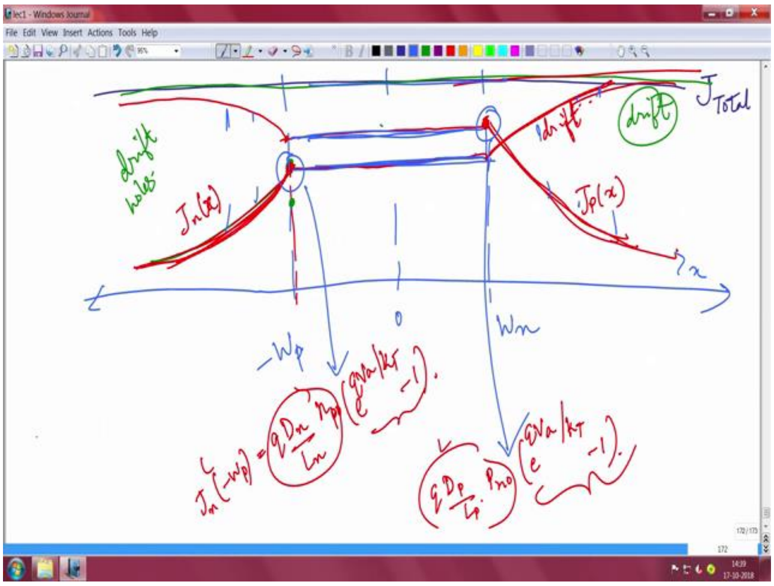

So, I will again plotted here, so this is your x this is your x. So, this is the 0 this is your Wn this is a minus W p. So, what is happening is that your hole current is now diffusing like that right this is your J px hole diffusion current and this value I told you is qD_p/ L_p* p_{n0} * $e(^{qVa/kT}$ -1) that is the value ok. Similarly on the n side also your electrons will decay at this point you know this is electrons is on the p side sorry on the p side electrons are diffusing, so that diffusion kind also is depend on x.

At this point this, the value of the diffusion current because of electron at minus W_p that point this value is given by same thing here almost q D_n/L_n, because the electrons are diffusing this side into n_{p0}which is the baseline the background electron concentration is a minority into $e(^{qVa/kT}$ -1) the same thing only this part changes ok, the exponential part remains the same. Now these are diffusion components of current on either side.

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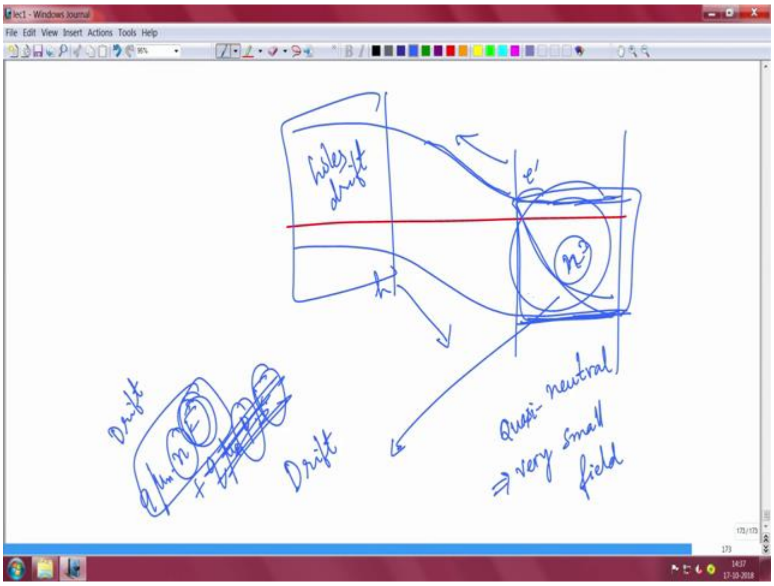

Now, if you recall a p-n junction band diagram; I am just drawing at equilibrium, but it is fine you can draw non-equilibrium also. You see now electrons are being injected from n side to p side and holes are being injected from p side to n side and they are decaying of course, on the respective size there I mean there holes are decaying here electrons are decaying here, so you are getting the diffusion current. But this region which is supposed to be a neutral region is not strictly neutral because, there will be some field, some voltage that will drop, there will be a very small field that will exist here and that is why these are called Quasi neutral region.

So, it is not exactly neutral and there is a very small field that exists there ok, there a very small field compared to this slope that slope is almost negligible. So, we write it flat, but there is a small field that is here very small field and it is called Quasi neutral, because some voltage is dropping here. So, because there is a small field here there will be a drift current also.

Now, drift can be because of both electrons and holes this is n type. So, there will be q mobility of electron times n times the small field plus q mobility of holes times the holes here into the small field. Now, the holes are minority they are decaying here the hole concentration is very small multiplied by very small field is almost negligible. So, minority carrier drift here at the holes drifting here is very negligible. But majority carrier n is large. So, even if the field is small a very large n majority carrier will make sure that the drift current; the drift current, because of electron in this region is not negligible.

Similarly, the drift current of holes in this region is not negligible, drift current is not negligible. So, those drift current components and there could be other components also like majority might also diffusion in small quantity right. So, all those components we will basically make sure that the total current here is constant. So, the total current here; the total current here has to be constant I will tell J because, the current density I am not taking the area J_{total}, the total current is constant, but the hole diffusion current on the n side is going decreasing like this.

The electron diffusion current on the p side is going like this. So, the respective drift current will be such that will be how, the respective drift current will be something like that let me is a different color may be the respective hole current the drift current. This is the drift current of majority electron and this is the drift current of majority holes here, drift of majority holes I told you there is a small field in a neutral Quasi neutral region this is drift of majority electrons on the Quasi neutral region.

So, the addition of this plus this plus this will make sure that the total current is constant. And I told you that within this depletion region this is the depletion region you know within the depletion region, there will be no recombination of current whatever current is at this point will continue through out here and whatever current is at this point will also continue there ok. So, let us look at their point again, so this is the hole diffusion current this is the value here whatever milli amp micro amp whatever.

This will not change in the depletion region, this will not change in the depletion region this will not change in the depletion region, so it will remain constant and actually your majority hole drift will start from here like that so the total is constant ok. Similarly the electron diffusion current that is happening here this value will not change in the depletion region because, in depletion region there is no recombination that is the idea. So, it will stay flat. Why this staying flat is, is staying flat because in depletion region there is no recombination. So, it is staying flat and so this current will actually increase from here this is increasing here I will increase from here.

So, does addition of this current and this current will basically give it a total as a fixed current, remember this current is drift of majority electron and this is diffusion of minority holes ok. So, if you look carefully the sum of this and the sum of this is actually the sum of any point here any point is the total current right. So, this plus this is actually the total current and you know this value is nothing, but this value which is this and this value is the same as this value everywhere is this to can I say that the total current.

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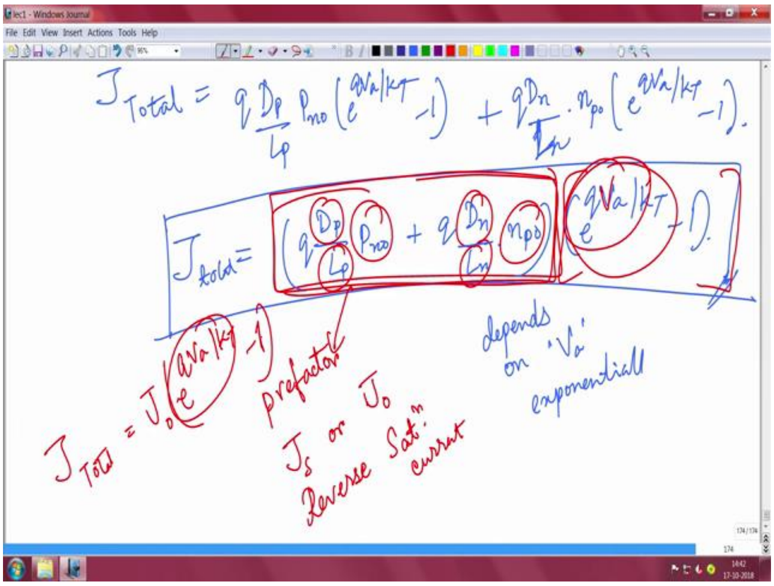

The total current now J_{total} is nothing but the current here plus the current here which means, the current this plus the current this is the total current. So, what is this current so can I add those as the total current, the current is qD_p/L_p that is hole diffusing on the n side p_{n0} $e(^{qVa/kT}$ -1) plus this is electron diffusing on the p side electron diffusing. Diffusion coefficient of electron diffusion length of electron minority electron based on the other side $e(^{qVa/kT}$ -1), again write it as ($qD_p/L_p * p_{n0} + qD_n/L_n * n_{p0}$) * $e(^{qVa/kT}$ -1) is given by the total diode current.

$$J_{total} = (qD_p/L_p * p_{n0} + qD_n/L_n * n_{p0}) \, e(^{qVa/kT} - 1)$$

Which is independent of x of course, current cannot depend on x it has to be constant everywhere the total current has to be constant. So, this does not depend on x, but it depends on the at voltage exponentially depends on applied voltage V_a exponentially, you see this quantity exponentially this pre factor which is not dependent on x or which is not dependent on voltage it only depends on parameters like diffusion coefficient, diffusion length diffusion coefficient diffusion length which are material parameter and the minority carrier concentration.

You know this pre-factor can be leveled as J_s or J_0 some text books call it J_0 some people call it J_s it is actually call reverse saturation current ok. I will come to why is it called like that later on it is called reverse saturation current and this value is typically pretty small like pico. But this is multiplied by large quantity because, this quantity becomes very large at as V is increased. So, I can write the total current $J_{total} = J_0\ e^{(qVa/kT} -1)$ this quantity becomes very large soon so one can also be neglected in forward bias.

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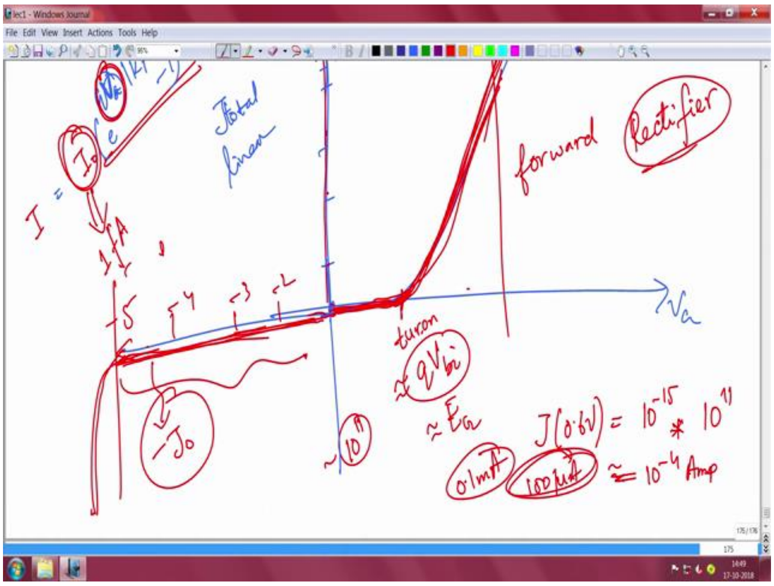

So what I am trying to say is that if I plot J_{total} versus V_a applied voltage look at the formula $J_{total} = J_0\ e^{(qVa/kT} -1)$, if you have V_a is 0 then e^0 is 1, 1 minus 1 is 0. So, it will be 0 so at 0 volt there is no current make sense. Now as you slowly increase V_a it will slowly increase ok, but in linear scale if this is linearly your plotting the linear scale which means 10 20 30 40 and so on. Then initially it will not show you anything it will basically is yet to turn on there is something called turn on, at some point it will turn on and then you will see an exponential change.

Actually this is already increasing here, but you cannot see it in the linear scale, you have to see in the log scale. For example, at this point current might increase from pico Amps to nano Amps, but if this scale is milli amp 1 milli 2 milli 3 milli 4 milli, then you cannot see a change from macro amp to nano amp or nano amp to micro amp right that is what looks like that. At one point it will turn on it is call the turn on voltage and it will increase exponentially, it will increase very exponentially this is a turn on voltage and the turn on voltage is almost equal to the built in voltage it depends on the built in voltage and hence the band gap.

If your band gap of the semiconductor is large the turn on voltage also will be large by the way. So for example, if this value I told you is very low suppose I take a value of say this is current density. So, suppose this is you know even if you take absolute current it will be I_0. So, suppose the absolute current is say 1 femto Amp 1 femto Amp is 10^{-15} Amp and this V_a is applied voltage is suppose 0.6 volt, then $e^{(0.6/kT}$ -1), 0.6/0.026 can be neglected is very small. This is equal to e^{22} and $e^{22}$is a very large number.

See e^2 is almost 10 is not exactly 10, but close to 10 you can say. So, e^{22} will be equal to 10^{11} almost slightly more than that or slightly less than that. So, you can say that total current at 0.6 volt is equal to 1 femto Amp which is $10^{-15} * 10^{11}$, which is equal to 10^{-4} Amp there is equal to 100 micro Amp. So, see from 1 femto Amp to 100 micro Amp or milli amp this is the same as point on milli amp. See from 1 femto amp to point 1 miili amp the current increased from this to that is a huge change in current, so it can increase exponentially it can increase exponentially in the forward bias right.

So, a small change in the applied voltage will lead to a very large change in the current. So, that is the beauty of our base there are many things that we will keep referring to when we are discussing p-n junction, I will also refer to how LEDs will work how detectors will work and so on solar cells and so on with respect to p-n junction equations ok. I will come to that in subsequent classes.

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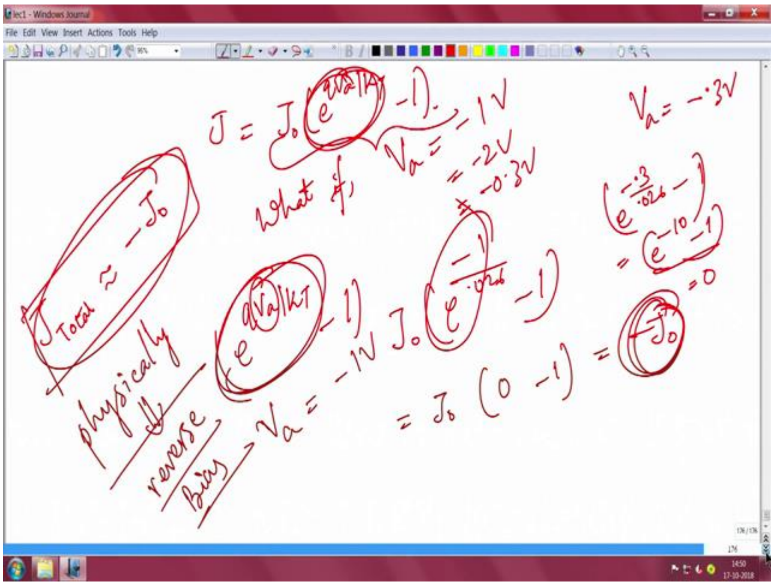

So now what again you have to think about here is that suppose J is equal total current J_0 what if the applied voltage is negative say minus 1 volt or say minus 2 volt or say minus 0 point 3 volt whatever what will happen then. So, you see this term $e(^{qVa/kT} -1)$ right. If you are V_a is negative then this quantity becomes very small very soon this quantity will become almost 0 right.

So for example, V_a is minus 1 volt how much will that be $e(^{-1/0.026} -1) * J_0$ this is equal to J_0 e to the power minus this will be like minus 20 I do not know this will be like minus 25 you know more than that. So, 1 divided 1000 divided by 26 is like minus 40 e to the power minus 40 minus 1, what is e to the power minus 40 almost 0 it is 0 almost right is 10 to the power minus like 20 or whatever right so this is 0.

So, 0 minus 1 is minus so this will be minus J0 which means at reverse bias voltage your current saturation current is the total current in the diode is actually minus J0 which is reverse bias current. Of course, if you have Va is very small negative say minus 0.0 at very small you know like minus even minus 3 volt, if you talk about that will be e to the power minus 0.3 by 0.026 that is like minus 1 that is like $e^{-10} -1$ which is 0 almost. So, essentially in reverse bias J_{total} is almost equal to minus J_0 because this term becomes very small almost 0.

So, in reverse bias essentially so if I plot this on the reverse this is on the forward bias are in increases right, on the reverse bias side the current is actually very small like this and that current is given by it is very small current that current is given by minus J0, it is the reverse by saturation current. So, on the reverse side say minus 5 volt this is minus 4 minus 3 minus 2 and also on. So, the current is very small on the forward side after turn on it will increase lot this is called rectifying behavior.

That p-n junction diode can behave as a rectifier because in one direction it can lead to a large current, in the opposite direction it will lead to a negligibly small current that is called rectification, which when a diode where a device allows current to flow in one direction, but does not allow current flow in another direction is called rectification. So, a p-n junction diode can behave as a rectifier and this is what is very obvious from this expression and the mathematical analysis at very large voltage the diode will break down like this.

We will come through a breakdown little in an one of the next classes sometime maybe next to next class also, diode will break down eventually at higher voltage that is the different phenomena. But until that point until that point your current is very low it is given a minus J0 like pico m for femto Amp on the other side this can can be very large like milli amp or amp. So, essentially you are able to rectify this that is why p-n junction diode is called you know a rectifier it can work as a rectifier. Now I told you that you know if I plot a negative voltage here this quantity becomes almost this, but physically what happens can you also look at reverse bias junction physically can you look at reverse bias junction physically does the question, so look at that now.

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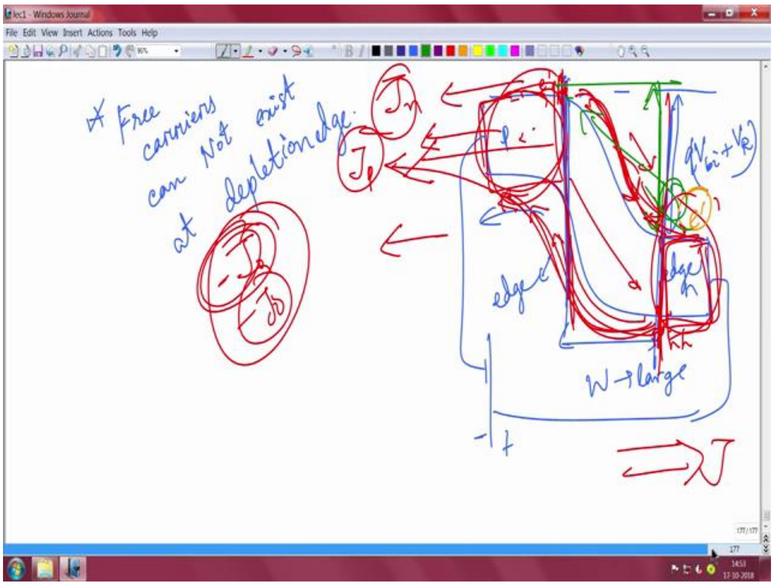

So, I will draw a reverse bias junction a reverse bias junction the depletion becomes larger. So, this built in voltage has become large by $q(V_{bi}+V_R)$ it is a large which has increased now, because this is p type connected to negative this is n type connected to positive carriers are being drawn away. So, of the depletion region the depletion region has also become large in reverse bias what is happening is that holes are not injected and this side right.

There actually taken away so this edge this is a edge right edge of the depletion region this is an edge of the depletion region this is also edge of depletion region, at the edge of the depletion region we assume that free carriers that is electrons and holes electrons and holes cannot exist at depletion edge. The region we assume that is that we assume that at this depletion edge there cannot be any mobile electrons or holes at this edge. I mean you when I say electrons or holes I mean minorities specifically because, the moment there is a carrier it will be swept away the field you see this field is huge.

This is a huge slope so and p side what is minority is electron. So, if the electron happens to come here at this edge it will be immediately swept at to the other side and on the n side what is minority hole, if the hole comes at the depletion at somehow it will be immediately swept away this side, because for hole this is lower energy it goes like that for electron comes like that right. So, immediately it will be swept away that immediate sweeping away of the minority carrier is what contributes to J_0 - J_0 current, that is what is contributing to - J_0 current. You see any minority carrier that comes at this edge electron will be swept away this side, which means the carrier current flow is this side.

Similarly any hole that minority comes at the edge will be swept at to the other side which means the hole current is also to this side. So, both this electrons and holes current are to the negative side that is why it is minus J_0, which means the reverse saturation current is in the direction opposite to the forward current. When you apply a forward bias if you remember electrons are injected from this side to that side holes are injected from this side to that side, the net current is on the positive x direction if you remember in a forward bias. In reverse bias the current is very small and that current is in this reverse direction J_0 is $-J_0$.

So, why will the minority carrier come at this edge, the minority carrier might come at this edge because of random diffusion within this minority might diffuse and they might randomly come here you know. So, that will get diffuse similarly minority electron here minority hole in this card randomly diffusion and there might come here, so there will be swept away on the side. But there is no majority injection holes cannot be injected from here to there because; there is a huge barrier electrons cannot be injected from this side to that side because there is a huge barrier huge barrier.

So, electrons cannot be injected holes cannot be injected it is basically minority that is suddenly coming here and doing pushed away ok, now on as a suddenly is been basically diffusion. So, here also you can solve the boundary condition in the sense that you know in the solution of the forward bias junction condition.

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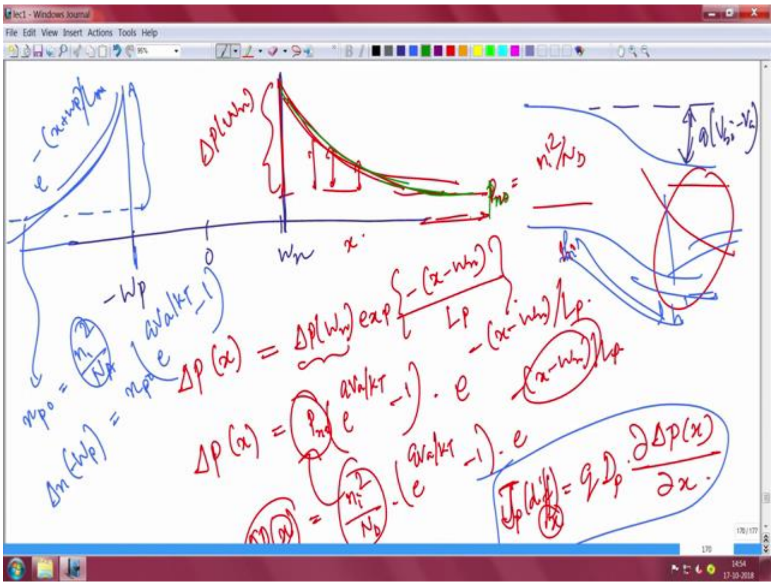

In the solution of the forward bias when we are discussing the forward bias condition here. There is a boundary condition that you know at large distance eventually your carrier concentration will become equal to the background carrier concentration right at large distances. So, that is one of the conditions for in this case when you have a minority in reverse bias junction.

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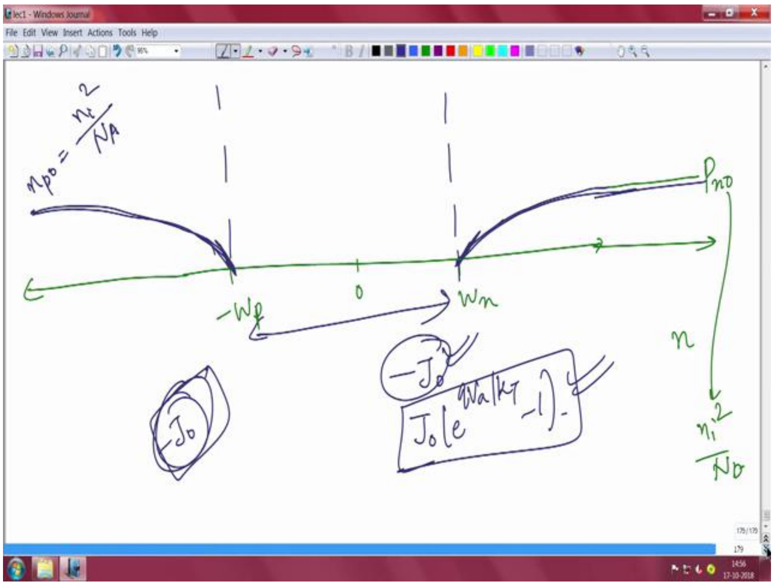

For example here so what is the condition that will apply, so essentially here I am drawing x this is 0 this is W_n this is minus W_p, the total carrier concentration at the depletion edge here has to be 0, but far away from the junction far away from the junction the carrier concentration this is n side. So, the minority carrier hole concentration is given by p_{n0} which is n_i^2/N_D ok. So, far away from this junction this is here, but close to the junction it will be 0. So, at the edge the carrier concentration is to be 0 so it will go like this.

You can actually solve the continuity equation with the appropriate boundary condition and get this ok. Similarly, here it will be base line will be n_{p0} which is equal to n_i^2/N_A at this depletion it will be 0 at this edge of the depletion it will be 0 and the derivative of this point and the derivative at this point will give you the respective current that will that might go and this is the total concentration is 0 here. And, that current if you add up minus J_0 only that is the same thing that you will get ok.

You can solve the appropriate continuity equation at the boundary condition that at this point it has to be 0 at this point it has to be 0 far away it has to be p_{n0} far away it has to be n_{p0}, then you will get the same value of the current this depletion has become larger by the way. So, essentially you know the reverse saturation current is minus J_0 which is very low and the forwards current is this J_0 e($^{qVa/kT}$ -1) this is a total forward bias current this is a reverse bias current.

This flows in the positive x direction this flows in the opposite direction and this is a diode that behaves like a rectifier. So, this is a p-n junction that can behave as a rectifier and there are many things actually.

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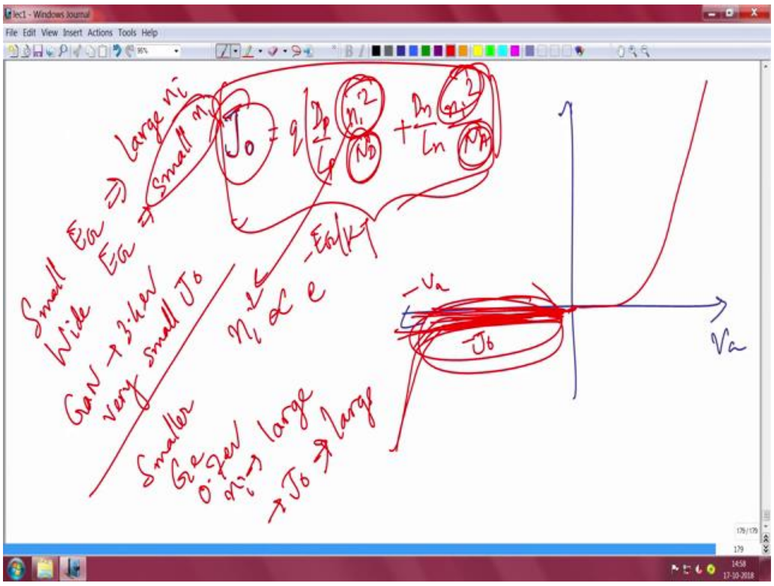

If you look at this n naught for example; J_0 this reverse saturation current also you know the reverse saturation current manifests something like this right, I told you this is J this is your for the voltage that you are applying. So, on the forward bias junction of course you know you will get like this, on the reverse bias side you will get very low current like that. So, this is your minus J_0 so very small current actually almost you know very small this J_0 actually is $(qD_p/L_{p)}$ $*p_{n0}$ which I can write as n_i^2/N_D + (D_n/L_n) $*n_{p0,}$ n_{p0} is $n_i^2/N_{A.}$

$$J_{0\,=}\,[(qD_p/L_{p)} * n_i^2/N_D + (D_n/L_n)\, n_i^2/N_A]$$

So, it depends on doping of course if I increase the doping then you are reverse saturation current also will decrease, if I want a very low leakage or a you know when I block the block voltage on the using this diode on the reverse side on the reverse side I am blocking the voltage you know I am not alloying current flow. So, if I want a low leakage where here is this quantity has to be lows of the doping can be slightly high, but more than that it depends on n_i depends on n_i and n_i^2 depends on Eg to the power minus band gap by k T. So, a small band gap leads to a very large and I intrinsic carrier concentration if you remember in a large band gap leads to a very small n_i if you recall.

So, essentially a larger band gap material like Gallium nitride with a band gap of 3.4 eV will have very small n_i and hence your reverse current will be very small should be very small right. Whereas, for a smaller band gap material say if I take a smaller like germanium 0.7 eV. So, n_i is large n_i is very large then your J_0 also is large, which means this reverse current this reverse current is large. So, a wider and material will have a better rectifying property than a narrow band gap material because, a narrow band gap material will have a larger leakage current or larger reverse saturation current. So, please keep that in mind and this is a very important point actually to the design p-n junction diodes.

For example, this reverse leakage current it was getting with which you are essentially blocking the voltage is very important in power devices power electronics or the photo detector this is called the dark current without shining like this is the current you are getting. So, this leads to noise so if you can lower the noise, the noise will become less and your performance will improve, so you want to use a wider band gap material for many application like that. So, we will wind up the class here so we have finished of the p-n junction in non equilibrium under application of forward and reverse bias what happens we have derive the expression for the current.

So, this is in an essence the p-n junction fundamentals that we had to learn to be able to understand many other devices, the forward bias and the reverse bias current expressions we have derived, the physics of that we have explained the diff diffusion component and all. The next class the beginning we will also dwell upon a little bit more on the p-n junction, we will think about the p-n junction little more, we will contemplate we will ponder about it with reference to devices like led’s or photo detectors or solar cells we will discuss some basics of p-n junction ok. We will discuss some basics of p-n junction and how you know in there are some exceptional cases of p-n junction like high injection effect and so on.

So, those things also we will discuss a little bit and after that we will move to before we go to metal contact with semiconductor which is Schottky junction and so on. We shall cover one more very important aspect of p-n junction that is breakdown, how does breakdown happen in p-n junction and capacitance a p-n junction also as a capacitance on it is own. So, to the capacitance voltage or c v profiling those things also need to address. So, probably we will spend next one, two lectures on this entire things ok. So, today we will end the class here we will meet you in the next class again.

Thank you for your time.