Fundamentals of Semiconductor Devices
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Lecture – 17
p-n junction under bias

Welcome back. So, we have concluded the last lecture on p-n junction in equilibrium, we had expressed the you know the expression for depletion region built in potential and so on and we say the today we shall start p-n junction under bias. So, when we apply voltage what happens? There will be current flow. So, today we analyze that and only then we will understand how devices work right till.

So, till now we had set the base for essentially how to calculate the depletion region, the built in potential, the field the you know the and respect to doping with respect to different band gap. So, now we will actually start dynamic the conditions, the non-equilibrium conditions when you apply voltage how does a p-n junction behave ok.

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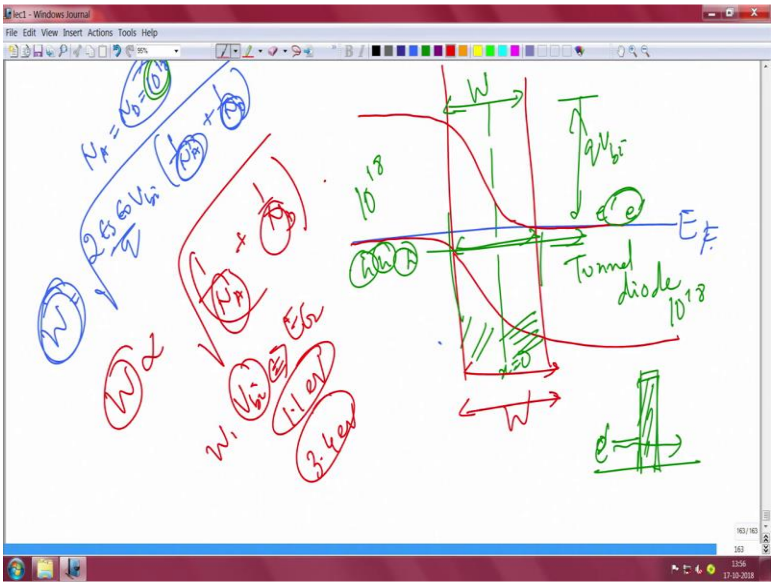

So, we will come through a white board if you recall the last slide you know the last lecture was that, I told you that the depletion region that forms in a p-n junction which is this, the depletion region will become wider if you are if you doping is lighter.

So, if you have a lighter doping, that will become wider because it depends inversely as $(\frac{1}{N_A}+\frac{1}{N_D})$ squared of that and then there is of course, there is order terms. So, if a doping becomes larger than you depletion also becomes smaller right. So, that is we have talked about and also told you how depletion region and built in potential depend on the band gap right a wider band gap, material will also have a larger built in voltage.

So, if you have a silicon of 1.1 eVand gallium nitride of 3.4 ev, as the band gap then the built in voltage for silicon will be always smaller than that of gallium nitride right. So, we have done all this things in the study conditions of p-n junction, now we are ready study p-n junction under bias right. So, I will draw the; I will draw the equilibrium band diagram we will start from there.

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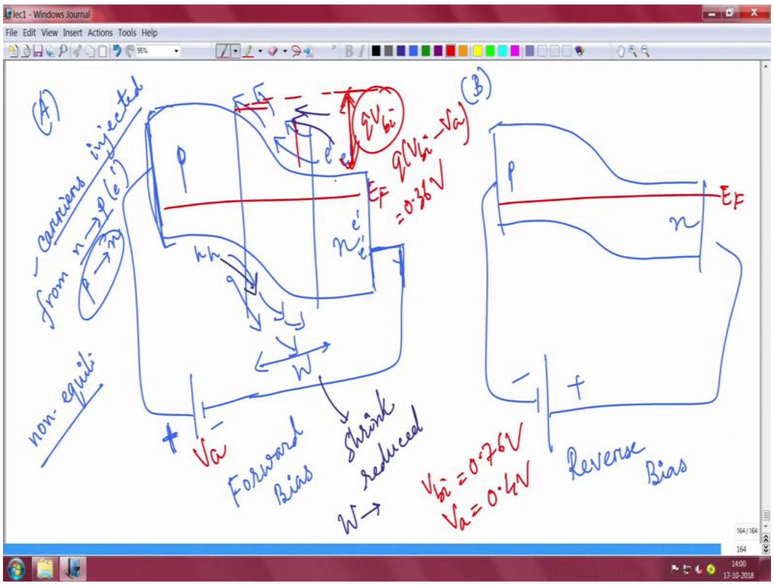

So, suppose your this is your Fermi level right, this is equilibrium. So, the Fermi level is same everywhere; now this is your n side, this is your p side. So, there can be two sort of bias configurations that you can apply, one is that you apply a negative voltage on this side and positive voltage on this side ok. This is call forward bias; this is call forward bias configuration of a p-n junction, you are putting negative to the n side positive to the p side. And of course, there is the order condition where you know you can did the opposite, which is this is a Fermi level and p n this is n sorry.

I am so, sorry actually this is this is p sorry this is n. So, I am putting positive to p I am putting positive to p and negative to n. This is called forward bias positive to p n negative to n and then this is p this is n. So, I will put negative to p and positive to n, this is called reverse bias, reverse bias mode or reverse bias configuration of a p n junction ok.

So, the reason we call it a forward bias in this case; this is case A for example, and this is case B. So, we will analyze them separately, but we can I also derive expression for the current. When I say forward so, the point is that whenever you apply any voltage whether it is a in a forward bias mode or a reverse bias mode, the thing that happens is that the equilibrium is disturb now. So, the Fermi level will no longer with the same everywhere, because current will start the flow. So, what happens in forward bias is that.

In forward bias you are putting a positive contact to p side. So, there are holes here the p side has many holes and the positive bias will pushed the holes away. So, holes in the valence band will try to be pushed away to the other side and you applying negative bias to the electron to the n side. So, the electrons will be pushed away by the negative bias so, the many electrons in n side. So, the electrons will be repelled and they will essentially be trying to go through the other side. In other words we can say that carriers are getting injected from carriers are getting injected you know the majority carriers are getting injected from n to p n p to n.

Carriers are getting injected from n to p electrons are getting injected and from p to n holes are getting injected. Why is that? Because you are applying a negative bias, negative voltage the terminal of the batteries connected to the n side, the positive terminal of the batteries connected to the p side. So, carriers are injected the majority carrier of electrons from n side are now pushed the p side and p has many holes; the holes are being pushed the n side, it is a case of non-equilibrium of course, it is the case of non-equilibrium now.

And when they cross over here will what will happen to that, is that the depletion region which was earlier there W that depletion region will now shrink or reduced. The depletion region will reduced because, now more carriers are being pushed or injected from n side to p side p side to n side. So, the depletion region will now shrink. So, what was earlier W will now become reduced to some other value. And secondly, if you remember there is this built in voltage that we had qVbi.

That built in voltage will also now reduced because, you are applying a voltage and your injecting carrier. So, the built in voltage will reduce from qVbi to (qVbi-Va), where Va is the applied voltage. So, suppose your built in voltage, your built in voltage was suppose 0.76 volt and the applied your applying a voltage of say 0.4 volt then the total this drop across the p-n n side will now become 0.76 minus 0.4. So, 0.36 it will become 0.36 volt this drop will reduce. So, if I go the different thing.

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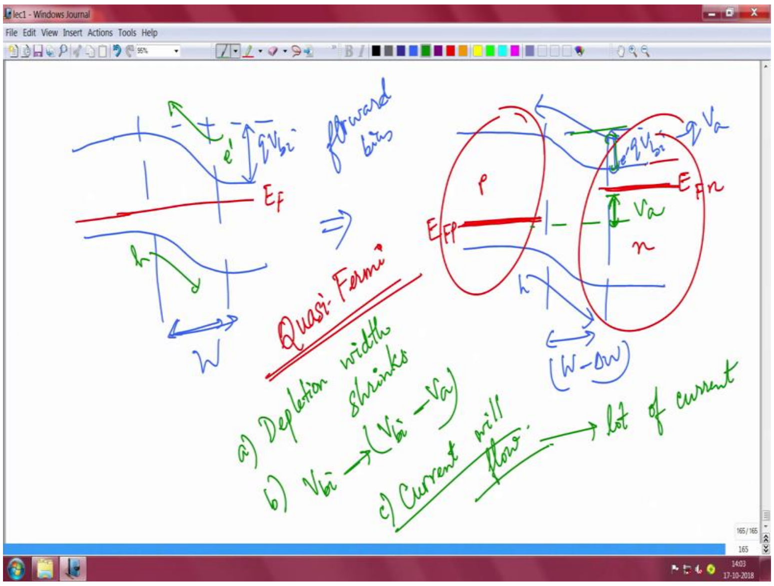

So, essentially initially you had something like that a Fermi level right sorry you had a Fermi level right and then you had conduction and valence band like this. So, this was equilibrium; this was qVbi, and this was your depletion region for example, W. So now, if you apply a forward bias, if you apply a forward bias what will happen is that, your depletion region your built in voltage will reduce.

So, this will have reduced to qVbi - q applied voltage and your depletion region also will become smaller it will become W- ΔW, some shrink it has happened ok because, now carriers are being injected to both sides. Of course, when carriers are injected now the there will be lot of current that will flow that is something will very soon come to. But, before that we should pause and reflect that your Fermi level will now be different because on the. So, what we do is that, we introduce the concept of a Quasi Fermi level.

Essentially you know you have several things now. Your you have a non-equilibrium and there are different you know the different concentration the electron and hole concentration will vary over a position. So, hole side will have a Fermi level of its own I call it E_{FP} and the electron side will have a Fermi level of its own I will call E_{Fn}, this is the Quasi Fermi level which means the Fermi level locally your is the Fermi level. So, this local Fermi level will tell you the hole concentration here.

This local electron the Fermi level will tell you the electron concentration here. So, this is the local Fermi level and the difference of this two; the difference of this two is your applied voltage. The difference of the two Quasi Fermi level on both side is your applied voltage which is why you are total voltage drop is the reducing by that the amount also ok. So, Quasi Fermi level is essentially the local Fermi level, that will tell you precisely at what position you have the different concentration of electrons and holes. And, if you do not apply bias, then the two Quasi Fermi levels will merge into one Fermi level and your Va will be 0 because, that is your applied voltage is no longer there right in equilibrium.

So, in forward bias what is the first thing? One is that your depletion width depletion width shrinks. So, it becomes smaller because now carriers are getting injected number 2, thing that happens that, is that the Vbi gets reduce to Vbi- Va. And, thirdly now current will starts flowing of course, right and what are the different components of current that will flow will come to that very briefly, now current will flow. So, this is your forward bias case and forward bias, you will have a lot of current, lot of current will flow, lot of current will flow. And whatever the reverse bias case situation I have told you right.

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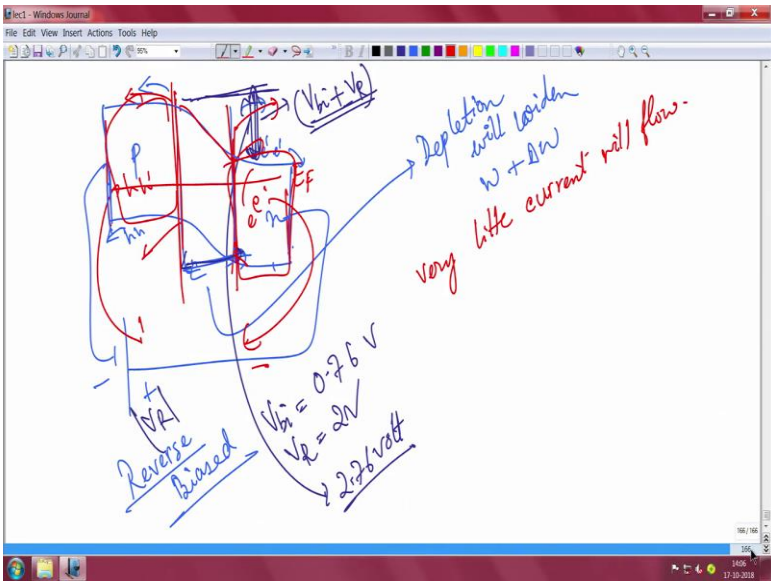

So, in reverse bias for example, I told you that you know you have a Fermi level for example, it is not straight here, but suppose I have a Fermi level and then I have a conduction band like that, valence band like that now this is p side this is n side. So, what is your reverse bias? Reverse bias is that you are applying a negative voltage here, positive voltage here. So, this is your reverse bias a reverse bias p-n junction. So, what does reverse bias p-n junction have? Now there is a negative voltage is applied the holes.

So, the holes we will sort of be there will be you know attracted this side, and these are electrons and you applying a positives the electrons are not here sorry electrons are here, in the conduction band electrons will be attracted to this side. So, essentially the depletion the electrons and holes are being pulled up away now from this side and this side. So, the depletion will widen now, depletion will widen; depletion will widen. So, what was initially W will become now W plus Δ W it will increase and this barrier.

This barrier also will now become large by qVbi, if you applying a reverse bias voltage of VR, this is the you know the absolute magnitude and talking about than this barrier will now become built in voltage Vbi plus V reverse both are positive ok. So, for example, initially the built in voltage was 0.76 volt and you applying a reverse bias of say 2 volt, then the total voltage drop here will be 2.76 volt. So, at your depletion will become wider now, your barrier also will now increase because carriers are pulled away carriers are pulled away from this junction now, because you applying a negative voltage here positive voltage here very low current will flow very little current will flow actually very little current will flow.

Do you know why very little current will flow? It is not like your electrons from this side will come out here, holes from this side will come out here and your p n n regions will completely become depleted no its not like to is not going to happen that is not possible. Its not like you have a p n junction when you connected reverse bias and all the electrons and holes from the p n n side become finish it is not like that. Then that would be a easy way of un doping a material no that it is not possible.

So, what will happen is that, you will have a very little current flowing because there will be no carrier supply this barrier will increase and carriers will be pushed away from this barrier. So, you know at the edge of the depletion essentially we will have no free carriers and your current will be very low, we will come to the exact analysis in a bit. So, now let us talk about the forward bias. So, that we can understand the current we are talking about forward bias, we will talk about forward bias.

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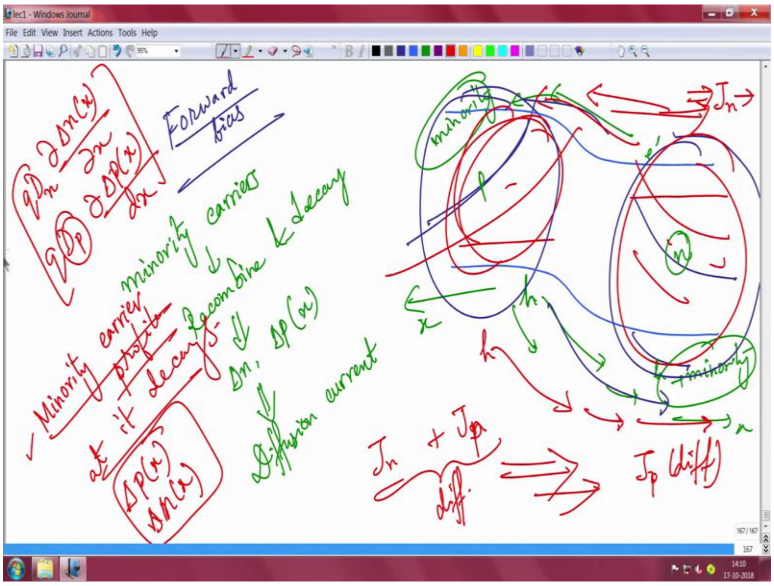

So, the first thing we need to know in doing forward bias is that. So, I will draw a forward bias condition. So, you have conduction band, your valence band, this is your Quasi Fermi level on the p side, this is the Quasi Fermi level on the n side. So, you have electrons injected this side holes injected that side. This only happens in forward bias in reverse bias this does not happen, because reverse bias you are not injecting any carriers.

So, what will happen is that, electrons on the n side a majority there will injected to the p side. So, they become electrons become minority here. Similarly holes are injected from here to there, once the holes reach the n side they become minority here. The moment electrons become minority on p side and holes become minority on n side.

The minority carriers will do what? Minority carriers will recombine minority carriers will recombine and decay and the moment minority carriers recommend and decay you have a Δ n Δ p sort of a thing right they will decay over a position. This is x this is x they will decay as a function of position. So, that decay will give rise to diffusion current right a diffusion current that is there because holes are on the n side they are decaying. So, holes will decay here that will give a hole diffusion current. Electrons are sent to the other side electrons will decay here, that will give an electron diffusion current right.

So, there will be two diffusion current, one is hole diffusion current because that will holes will diffuse here electrons become minority on this side and they will diffuse here. So, there will be electron diffusion current. Now electrons going from this side to that side, means the total electron current Jn diffusion is going to this side positive x. And holes being diffusing the injecting from this side to this side, the travelling this side means that the hole diffusion current is also to the right. So, both electron and hole diffusion current, the both electrons and hole diffusion current is to the positive x axis you agree now.

Electrons are going from this side. So, the or the electron diffusion current will be on the positive x axis. So, our job is then to find out the minority carrier profile; the minority carrier profile as it decays as it decays into the respective side. [FL] The electrons decaying on the p side and holes decaying on the n side; if we can find out the minority carrier profile which is Δ p x on the n side it will decay, and Δ n x on the p side it will decay. If you can find out then we can quickly find out the electron diffusion current as q the electron is diffusing on the p side you know.

So, q D n Δ n x by dx, and the hole diffusion current on this side because the hole is diffusing will be q D p is the diffusion coefficient of hole by the way Δ p x by dx on the p side. So, if you add this two current that will be your you know sort of the total diffusion current that is happening here that is what you want to find out all right. So, how do you find out now?

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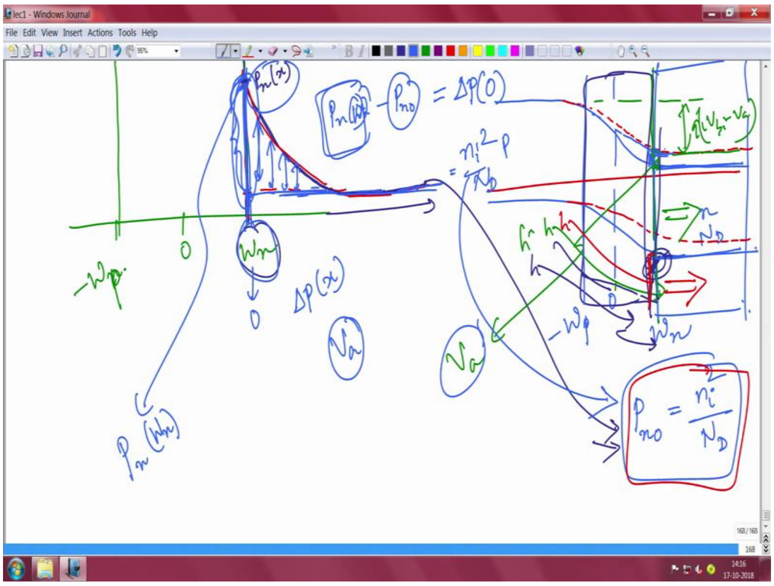

So, if you recall initially your with an equilibrium before any application of bias before any application of bias, you had a band diagram like that it is a same band gap my drawing may not be exactly accurate, but this is the same band gap. So, I will look at the n side, this is a depletion ok. So, the edge of depletion here this is called the edge of depletion. So, this is 0 this is x equal to w n this is x equal to minus w p. So, an x equal to w n at the edge of depletion, the minority carrier concentration is the same everywhere ok.

And, that minority carrier concentration is hole here in the n side p n that is your minority carrier concentration in equilibrium p-n 0 I will put p n 0 means minority carrier whole concentration in equilibrium in this neutral n region that is baseline your the background p type the minority p type in n type, that is n I square by the doping that you have ND is the doping here. Similarly, the minority carrier electron concentration on the p side will be you know n i square by n a. So, we will only focus on this n side ok. So, the same thing will exists on the p side we will only focus on the n side the same thing will have exists on the p side ok. So, a focusing here so, this is your minority carrier base line concentration; now the moment the moment you apply a forward bias, your barrier reduces you know.

So, your barrier height will reduce like this. So, your barrier height has reduced it has become qVbi minus Va which means the this point you know has risen by a value of Va.

So, the minority carrier concentration here will now change now your injecting holes you know of course. So, your injecting holes. So, holes will have a large concentration at this edge and as you go further and further to the bulk to the inside, that majority carrier concentration will decay ok. So, if I draw the minority carrier concentration profile. So, for example, this is the x axis this is your 0 point, this is your W n the depletion and this is your minus W p on the other side ok.

So, depletion so, you see at x equal to W n here. So, the holes are essentially coming to this side you know. So, at this point and we assume that inside the depletion there is no recommendation that is happening; that means, all the carrier density is preserved. So, whatever hole your injecting is everything is unchanged here and over here it comes here which is this edge, this edge is actually this edge. So, at that point your hole concentration minority hole p-n; p- n it is a function of x by the way, at this point it is p-n 0 0 this is the high value and eventually this is start decaying.

It will not eventually it will immediately start decaying right it will start decaying and eventually it will become constant that value that will it will become this is the equilibrium value, this is the baseline value which is given by this. This is the equilibrium value of minority holes in the material that to that value it will decay, to that value it will decay. Why is it large at this point? It is large at this point because holes are being injected, they are arriving in fresh quantity in large quantity here and they are decaying as you are going right. So, at this edge they are very high and they are decaying ok.

So, the excess carrier this is the baseline this is the need not the neutral this is the background carrier p type the minority. So, essentially the excess carrier concentration is this, this, this, this, quantity is your execs which means p-n that you have at this point total 0 let me again rub it up. So, the excess carrier concentration is this quantity this because this is your background you know this value. So, p-n 0 minus p-n 0 and p n 0 this is your this is your background p type I mean the minority carrier the holes in the n type and this is your excess carrier at 0.

So, the total carrier at 0 the total carrier at 0. So, the total carrier at 0 minus the base line or a background carrier gives you the excess carrier. So, this is your excess carrier Δ P, its called Δ p excess carrier at x equal to 0, but there excess carrier is decreasing. So, its a function of x. So, Δ p we will change as a function of x that is what we want to find out. Now the question is what is this value? The total minority carrier hole value at x equal to 0 at this x equal to 0 [FL] I am considering this as 0 as the reference actually this is W n by the way when I say this point is 0, I am talking this is the reference, but its actually W n here, but I was taking this is reference, but you can take W n also ok.

So, I will can either take it as 0 W n. So, let me take it as a W n only W n. So, this is then W n that is ok. So, at this point what is the excess carrier, where is the total carrier concentration that you have? So, the equilibrium baseline hole concentration is a minority in the entire is given by ni square by ND which is this. Now because you are applying a forward bias voltage of Va that is your forward bias voltage your energy band has ray raised by that amount your energy band has raised by that amount. So, there is a difference between of Va between this point and that point right.

And any change you know the change in carrier concentration depends exponentially on the change in the band on the band position ec or ev right. So, essentially the total carrier concentration let me go to a different slide here again.

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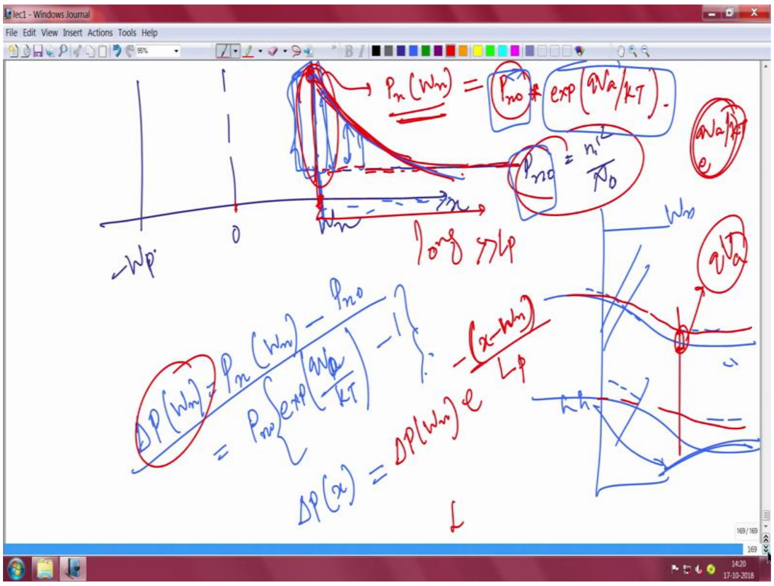

So, if I talk about this again this is your x, this is your 0, this is W n this is minus W p. So, I told you that this is your base line that is p-n 0 equilibrium ni square by ND and I told you that the total because the holes are injected, there will be a excess that will be total carrier here which a very high it will decay eventually it will decay like this and it will go and become same as the background right.

So, this quantity this point is your total carrier concentration at x equal to W n or x equal to I mean if you can take it has 0 that is different thing this value will be this baseline value that you have which is p-n 0 this is your base line value; that baseline value has been raised to some amount you know that amount is this multiplied by exponential of whatever voltage you have applied by k T. Because as I keep telling your conduction band initially it was like that right, but at the forward bias when you apply the conduction band has shifted.

Your conduction band and valence band has shifted right by that amount. So, your minority carrier concentration will have increased by that amount or a majority carrier concentration would have decrease by that amount there is a holes and now getting injected to the other side and the holes this is the depletion W n. So, the holes are the maximum here because there is no carrier recombination that takes place in the depletion. So, the holes are maximum here and they will decay now there will decay now that is what is happening they are decaying.

So, at this point the total carrier concentration is the baseline concentration, times exponential of whatever voltage you are applying by k T that is how it has increase because you know because essentially if you have this point this point and your it has increased to this level, then at this edge you know this point and this point is a shift that is q Va. So, a minority carrier concentration we will decrease by exp(qVa/kT) the majority carrier will decrease. So, the minority carrier increase by the ok. So, that this is the total this is the total hole concentration here and I told you that the baseline concentration is this to which it decays. So, the excess carrier concentration is this. The excess carrier concentration is the total hole concentration at x equal to W n minus the base line.

So, this is given by Δ p at x equal to W n this is given by p n 0 exponential of qVa that your applying by kT minus p-n 0. So, I can take it out minus 1. This is your excess carrier concentration at this point this is your excess carrier concentration at that point and then excess carrier concentration will now decay with position. So, Δ p x at any point x at any point x will be the excess carrier here please remember the excess carrier here which is this Δ p W n and then it will decay exponentially which is e to the power minus because this is the reference you know.

I mean I am taking this as 0 and this is W n. So, it will be minus x minus W n by the diffusion length Ln L p this is p type you know hole not p type holes are diffusing you know. So, its the diffusion coefficient of or the diffusion length of holes matter. Lp refers to the diffusion length of holes. So, how far the hole will diffuse before it is a combined this is the diffusion coefficient of hole ok. And this x minus W n comes because I am shifting the origin from here to there, that is why it is coming like that.

So, essentially it is decreasing exponentially because it is a long diode I am assuming it is a long diode, this length is very large when I say large it means it is much larger than the diffusion coefficient. If it is not if it is a short, then this will not decay a exponentially where this will decay linearly we can come to that little later, but as of now we assuming its decaying exponentially, but if it is a short diode it will decay linearly please remember that.

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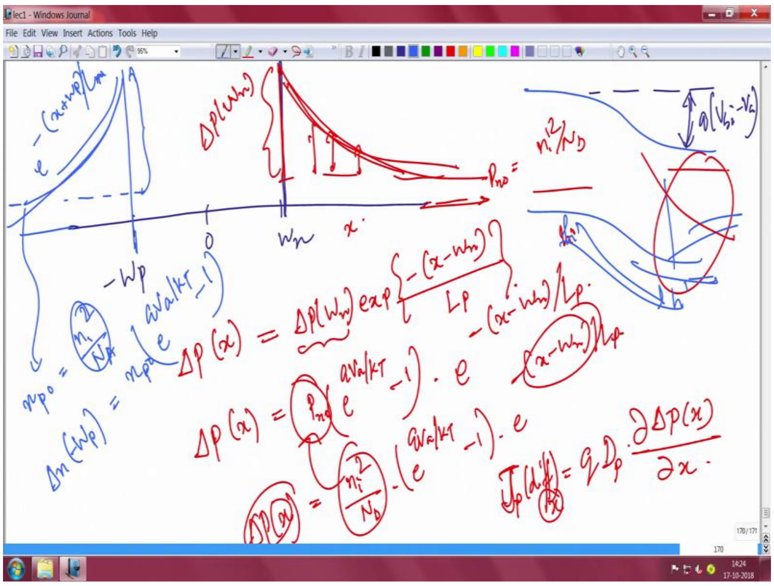

So, what is happening is that. So, this is a forward bias junction excuse me Quasi Fermi level. So, you are barrier has now reduced to qVbi minus q Va and if I draw the minority carrier profile 0 W n minus W p. The minority carrier profile is that is decreasing and becoming the baseline. So, this is your p-n 0 which is equal to ni square by ND this is your excess carrier at W n and it will decay here. So, at any point at any point x the excess carrier concentration Δ px is the carrier concentration here times then exponentially decay, which is

$$\Delta p(x) = \Delta p(W_n) \exp\left\{-(\frac{x-W_n}{L_p})\right\}.$$

So, I can write that as Δ p x I can write this as if you recall from an last slide I can write this as this ok. So, that

$$\Delta p(x) = p_{n0}\ e^{({qV_a}/{kT}\ -1)}\ e^{-({x-W_n}/{L_p})}$$

Of course, p-n 0 can be written as ni^2 /ND x e $^{(qVa/\ kT\ -1)}$ x e $^{-(x-Wn/Lp)}$. This is your minority excess hole type minority carrier concentration that is decaying on the n side because they are being injected from p side to n side this is the same as p 0 I mean the same thing right.

So, this is the function of x fx. So, if I take q D p the diffusion coefficient of hole on the on this side because holes are minority on the n side, times the Δ p x by dx this is a function of x. Then I will get the diffusion current of because of holes because of holes being injected to the n side, they are diffusing you know and they are diffusing here the decaying. So, because of that component what is the hole diffusion coefficient, hole diffusion current as a function of x? This is a function of x.

So, the whole diffusion current will be function of x, and it will reduce when it depends on the slope. So, it will it will basically as a function of x it will change right the derivative of exponential is also exponential. So, same thing is happening in the n side now on the p side now. So, if I go back to the case here. So, essentially on the p side here on the p side here electrons will be minority and they will decay they will decay to a baseline.

The base line is the electron minority concentration on the p side which is equal to ni square by NA and this excess carrier will be Δ n the electron because the electrons are being injected to the p side you know. At W minus W p this is your base line which is this times e to the power qVa by kT minus 1 same thing. And it will decay as e to the power minus you know x plus W p by Ln the reason is because this is a W p is negative.

So, L n electron diffusion on this side; so, both side it will decay and derivative or exponential or exponential.

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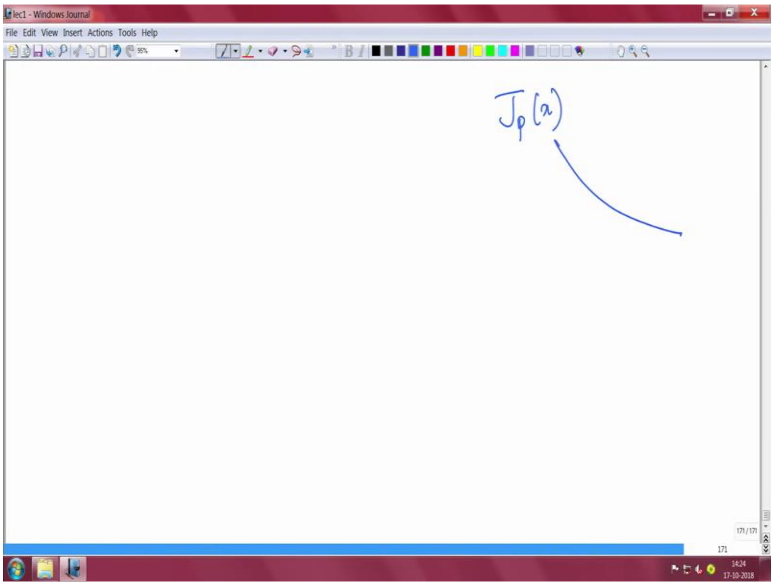

So, the hole diffusion current the hole diffusion current J sorry on the n side holes are diffusing as a function of x there will decrease if I plot the current. So, what will happen is that, if I take the derivative of their expression here you know of this expression, then I will get the hole current because of diffusion. Similarly, there will be a similar expression on the n side you will get the electron diffusion current on the n side.

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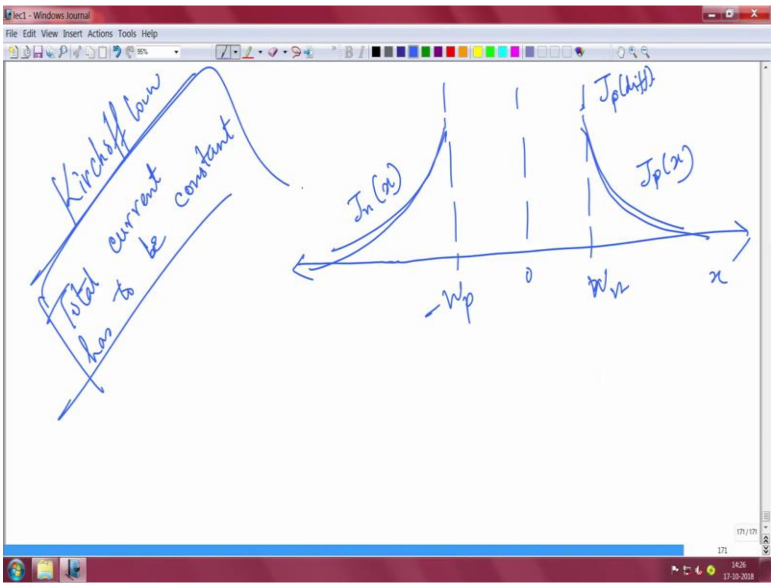

So, you know if you have I am plotting this is say x this is 0 this is W n, this is minus W p minus W p and your holes had been decaying. So, your electron hole diffusion current also will be a function of x, and it will decay like this. This is your j p of x and electrons will be diffusing on the other side. So, electron also will be function of diffusion current the function will be x. So, hole diffusion is decreasing as this, electron diffusion is this, but according to Kirchhoff law that you studied in your high school you know or your 10 plus 2 the total current has to be constant.

The total current has to be constant. So, what are the other current components then? We have to make sure that the current is constant the current cannot reduce exponentially like this. Of course, these are reducing exponentially which means there are other forms of current which will make sure that the total current is constant which will make sure that the total current is constant. So, what are those current components of current? That we will take up from the next class. So, we will wrap up the class here, what did we learn in this class today? In this lecture we have learnt that you know when you forward bias what happens when you reverse bias a p n junction what happens?

We are trying to derive a mathematical relation or mathematical expression to understand how carrier concentration varies as a function of distance, when you apply a forward bias. The minority carriers become decay on the respective side. Electrons are injected from n side to p side they will decay on the p side holes are injected from p side to n side. They will decay on the n side that decay is exponential for a long diode linear for a short diode, we only talking about long diode here. So, the decay we found out once we found out the decay the derivative of the decay is the current. So, the diffusion current on the both sides are now established.

But I told you that the total current has to be same. So, what are those components of current that will make sure that the total current is same? We will take their in the next class and we will finish up the current voltage analysis of forward bias junction in the next class ok.

Thank you for your time.