[Music]

So let us recap what we did in the previous lecture by properly doping impurities in a semiconductor you can make a part of it a p type and part of it n type one starts with ah one variety the entire wafer is is let us say is doped with a n type and then on top of that from one side one makes a more heavy doping of p type

So that the entire thing becomes p type

So if you have this diagram here the the p n junction is formed here from this side the doping is done first the entire thing is doped with n type and then from some portion it is made p type and then you have a junction out here what we generally show in diagrams in textbooks is this region is this region kind of this region

So this is a p type here and then n type here and then you have a junction in between this is the junction where this p type and n type overlap

So its a kind of one dimensional diagram in fact each line here is a layer this junction that you are seeing is one layer along which these two things are meeting and

So on

So this is it now we discussed that when these kind of different layers p type n type they meet at each point you have a lot of concentration gradient on n side you have lot of electrons and p side you have lot of holes and at the junction you have a huge concentration gradient and because of that some kind of diffusion takes place and if that diffusion takes place see this is our p side this is our n side you have lot many holes on p side and few electrons in this

So here you have n h is much much greater than n e

So the holes here are majority carriers and electrons here are minority carriers and on the n side you have n e much much greater than n h and

So electrons are majority carriers and holes are minority carriers and in this region no holes or electrons are shown and that is because of that huge concentration gradient which is formed and holes will diffuse from this left to right in this diagram

So holes will diffuse like this electrons will diffuse like this and therefore in this region all the electrons which were there and the holes which are coming they combine and both of these are destroyed similarly in this region lots of electrons are coming from right and the holes are there and these holes and electrons are combining here and that makes it a carrier free it becomes carrier free

So in this middle region you do not have electrons and holes because they recombine with each other but then in any region new whole electron pairs are created every time

So recombination takes place in general and this new whole electron pairs also are generated

So because of this concentration gradient because of this diffusion holes are coming in large number and combining with this thing but then the new ones are also created but even they are not present here why we had seen that when it happens in this way the charge density that gets disturbed

So if holes are coming from in this figure left to right and they are neutralizing this ah this electron free electrons here you have a positive charge appearing here and you get negative charge appearing here this is because the entire thing was neutral remember this whole p side was neutral and if holes only are going from here then what is left here is negative charge negatively charged ions are not compensated by the corresponding holes and similarly on this n side you get positive charges and because the electrons have gone from here and if electrons have gone from here then they will leave behind positive charges

So that creates an electric field and any whole electron pair that is generated that is created that comes up this electric field will sweep them in respective sites and this region is carrier free is not charge free it is carrier free that is the most important point to remember

So this whole thing is known as a depletion region that we talked we talk this whole thing is depletion region and what is depleted the charge carriers are depleted you do not have charge carriers ok

So the positive charges which appear in this depletion region and negative charges are appearing in this depletion region on p side positive charges on n side and i have shown different widths here x 1 here let us say this length is x 1 and say this length is x 2. So that relates to the doping densities ok

So here you can see that i have drawn purposely large density of holes here and on this side we have i am showing lower density of electrons here

So the doping need not be of equal level doping of n type and doping of p type can be of different concentrations and therefore when holes go and neutralize these electrons if it is a large density of holes on the p side then a smaller layer will neutralize a longer layer because the charge must be same the charge which is going from positives this p side to this n side and neutralizing

So what is getting neutralized and what is going to neutralize that should remain the same though that charge magnitude should remain the same and therefore if the whole density is larger here the width of the depletion layer to the left of this green line will be smaller x one will be smaller and x two will be larger

So these charges which appear here they will have their own fields this region is charge free here the total the row is zero here the rho is zero although there are

So many electrons but remember if there are electrons there are corresponding ions positive ions if there are holes there are corresponding negative ions and the rho is zero charge density in any small region if you make it is zero but in depletion region you have charge density which is not zero ok

So this side is x x i am saying this direction is x direction and remember this is our p side this is our n side and this p side extends up to here remember an n side extends up to here depletion region is depleted of the charge carriers but all those impurities that we have doped they are still there

So the p region and n region still meet at this junction

So as a function of x this is the charge density schematically

So as you go from left to right the charge density is 0 before the depletion layer here the charge density is zero

So you have this zero coming here and then when you enter the depletion region you have negative charge density

So i am showing this negative charge density by this line here and well we have taken a step function type of thing

So assume that the charge density is constant in this region

So this is the charge density here negative charge density and similarly as you cross that junction you have this positive charge region here and that is shown by this line

So you have positive charge density and then it goes to 0.

So if i say that my depletion layer is of width x 1 on the left x 2 on the right then this point is x equal to minus x 1 and this point is x is equal to x two and if this is the kind of charge distribution and remember these are layers when i am saying a line this line is in fact a layer a layer large layer

So if you have these kind of charge distribution then it creates electric field the electric field will be linear in the two region why do i say it is linear

So let us calculate it the charge density if i plot the charge density rho as a function of x

So i have a negative charge on this side and positive charge on this side this is rho equal to minus rho 1 this is rho equal to rho two this point is x equal to minus x one and this point here is x equal to x two this is the depletion region and i want to calculate the electric field what is the electric field

So if i plot electric field as a function of x how will it look like

So if i show you the depletion region once again suppose this is that depletion region and here is that junction which is x is equal to 0 and the charge density is rho it which is minus rho one this side and this is plus rho to this side and i need ah electric field at let us say this point here at a distance y

So what i do i divide this whole depletion region in different layers

So let us say at a certain point i draw a line this is at x at position x and then at x plus d x i again draw a line and consider this particular layer ok consider this particular layer the it is positioned at x and its width is dx now this layer you can treat it as a surface charge layer because the thickness is small

So this layer can be treated as a surface charge layer and the surface charge density that means charge per unit area of the layer will be rho times dx

So you have this sigma if you write sigma that will be rho which is minus rho 1 here

So minus rho 1 times dx this will be the charge density what i am doing i am treating this dx layer as a surface because the thickness is small

So how much charge per unit area is there and because of that what is the electric field at this point in front of the layer

So if the layer is large you remember if you have a charged layer of charge density sigma

surface charge density sigma and in front of that if you are asking for electric field that is sigma by 2 epsilon naught if it is vacuum here it is a silicon crystal

So that electric field d e 1 if i write that will be minus rho 1 dx over 2 times epsilon this epsilon is epsilon naught times k dielectric constant which is 12 for silicon

So this is ah the electric field because of this d x and then you integrate it then you integrate it over this whole region here to the left of the junction what you will get you will get e one equal to e one equal to minus rho one over two epsilon and then x one this d x when you integrate it will become this x one this length x one

So that is e one what is e one e one is the electric field because of this portion this portion how do i get electric field because of the other portion right of the junction let me remove certain part of it all right

So to get the electric field due to the other part what i am doing now is i am taking a layer here once again i take a small layer here to the left of this point where i am calculating the electric field ok because of this at this again the thickness is d x this thickness is d x and remember here row is row two plus row two

So what is the electric field due to this small layer that will be d e 2 and that d e 2 is is positive charge

So the electric field is towards right at this point

So this will be this equivalent surface charge density is rho two d x and divided by two epsilon and therefore e two is what is e 2 i am writing electric field because of this much because of this much it gives me electric field towards right

So that e 2 will be this is y

So rho two times y and divided by two epsilon and then i need electric field due to the remaining part part which is to the right of that point where i am calculating electric field

So if you look at that portion this portion here and once again if i draw that dx thickness here this dx thickness here the charge density surface charge density is same equivalent surface charge density but because of this the electric field here will be towards left

So it will be in negative x direction

So if i write that as d e 3 that d e 3 is equal to rho 2 d x that is the surface charge density equivalent surface charge density and then by 2 epsilon with a negative sign and if you integrate this d x what you will get you will get this whole thing is x 2 and minus this y

So if you integrate you will get minus row 2 and then the thickness and that thickness is x two minus y this divided by two epsilon you have to add all these three to get the final electric field at that particular point which is at a distance y from the layer from the junction towards right

So how much is that can we add it

So e one plus e 2 and plus e 3 e is equal to this and that is minus rho 1 times x 1 divided by 2 epsilon lets see if i have written it correctly e 1 minus rho 1 x 1 by 2 epsilon

So it is minus rho 1 x 1 by 2 epsilon correct then e 2 let us see what is e two e two is rho two y over two epsilon

So plus rho two y over two epsilon and then e three what is e three e three is minus rho two by two epsilon remember x two minus y

So first let me write minus rho two by two epsilon

So rho two over two epsilon with a minus sign and then you have x two minus y x two minus y simplify let me write row one x one equal to rho two x two use this let me use this rho one x one is equal to rho two x two remember the total negative charge on one side total positive charge on the other side should be the same

So that the total charge is zero

So i write this as rho two x two and therefore rho two over two epsilon this much i can take common then it is minus here and x 2 here right minus rho 1 x 1 is rho 2 x 2 and 2 epsilon and since i have already taken this common now this is plus y and this is minus x 2 and minus y which is equal to rho 2 over 2 epsilon and you see it is minus x2 and minus x2

So minus 2 times x2 then plus y and plus y

So 2 times y

So 2 also i can take common and then i have y and minus x two

So that is the electric field at that particular point

So if you plot this on the graph if this is my electric field if this is x and you plot this part remember we have done it for x greater than 0 to the right of the junction
So how will that look like what is y by the way y is just the distance from the junction
So you can write it x as a function of x
So you can also write this as e is equal to 2 rho 2 over or 2 is not needed in fact rho 2 over epsilon and then you have x minus x 2 okay this y is nothing but that the distance from that junction which is x equal to zero
So this point i called it y
So let us call it x this is x axis anyway
So it is this relation which we are plotting
So at x equal to x two electric field is zero
So if this is x two if this is x two here then the electric field here must be zero if this is x two the electric field here is zero and at x equal to 0 what happens at x equal to 0 if we write at x equal to 0 from this expression it is minus rho 2 x 2 over epsilon it is negative
So at x equal to 0 you have this point you have let us say this point which is minus rho two o x two over epsilon and then it is linear you can see that this is a linear equation in x
So it should be a straight line it should be linear and now the electric field to the left of the junction you can immediately write from here it was 0 at x equal to x 2 similarly it will become zero at x equal to x one and then at x equal to zero the field has to match and therefore that point that i have put there that will be the field at x equal to 0 and then it should be linear
So at x equal to x 1 this is x 1 the field must be 0 and then it should be linear in that region and therefore it should be like this from this side i have written this as the electric field here if you do from the left side you should get minus rho 1 times x 1 over epsilon if the same algebra is done but then rho one x one is same as rho two x two
So you get this
So the electric field is linear in the depletion region right to the junction and left to the junction they are linear
So e is rho 2 over epsilon and x minus x 2 just verify e is equal to rho two over epsilon x minus x two
So this is the electric field in the region x greater than zero it is like this what i am going to do now is to calculate potential
So at the junction let me take v equal to 0 at the junction suppose i take this junction here and i call this x equal to 0 and let me take v equal to 0 here you know we can always take v equal to 0 at our own choice
So we take this and ask what is the potential in this junction region depletion region what is the potential how do you get this the basic definition of potential difference is d v is equal to minus e d x and therefore it is minus rho 2 by epsilon x minus x 2 d x this is dv and if i need the potential i will integrate this it is minus rho 2 over epsilon x minus x 2 square divided by 2 plus some constant and if i imposing this condition then 0 becomes minus rho 2 epsilon x is 0 now
So x 2 square by 2 plus c
So that gives me c and hence what i have is v is equal to minus rho 2 over 2 epsilon and then x minus x 2 square and minus x 2 square its quadratic it is quadratic
So it varies it has to be since field is linear the potential has to be quadratic
So if this is x equal to 0 let me plot this v also if i plot it here let us say this is now x and this is now v this was e and this was x
So what happens at x equal to 0 as you see from this equation at x equal to 0 v 0 it should be like that we have already put that
So the potential here is 0 and then what is the potential at x equal to x 2 if this is x equal to x 2 what is the potential there it is rho 2 x 2 square over 2 epsilon okay at x equal to x 2 this goes to 0 and you have rho 2 x 2 square over 2 epsilon
So here it is somewhere here let us say and then its quadratic the slope is highest here electric field magnitude wise it is highest here and then the magnitude decreases the slope of this v should decrease in that fashion
So it should be highest here and then it should decrease and should then it becomes like this and beyond x 2 what happens beyond x 2 electric field is 0
So v becomes constant
So even beyond depletion region if you ask in that p n junction it will be like this

constant and similarly on the other side and how much is this how much is this by the way this is this rho 2 x 2 square over 2 epsilon naught 2 epsilon and on the other side on the left of the junction again the similar story and this will be a constant here if this is x equal to x 1 let us say if this is x equal to x 1 then it is some value and then it has to become horizontal like this and then this side it should be constant and how much is this this is rho 1 x 1 square over 2 epsilon just like this this is here it is rho 2 x 2 square same algebra everything same this will be this how much is the total difference in potential that total difference in potential will be rho one x one square plus rho two x two square and divided by two epsilon

So this is how the potential will vary in this pn junction and what about energy electron energy the electron energy will be opposite of this because it is negative charge the potential energy of electron will be minus e times v

So the potential energy of the electrons will be going up in this left region which is the p side and it will be going down in this right region which is the n side

So you had this conduction band minimum here and then the valence band maximum here let me draw it for two sides this is p side this is n side you have this conduction band lowest energy valence band lowest energy like this but then if that junction is made if the junction is made if diffusion is taking place if the electric field is generated if the potential has been generated the potential energies will be changed and therefore what will happen on p side remember potential goes down potential energy goes up for electrons

So on p side these levels will be raised on n side the levels will be reduced and what will you will have is ah diagram like this a diagram like this this is the conduction and this is that valence band energy

So the conduction band energies are here the valence band energies are here and So on

So that is how it will look like this is the n side this is the p side and this total difference this barrier difference this total difference is what we had calculated v naught the barrier we call it barrier because it opposes the motion of majority charge carriers barrier height is v naught and that we have seen v naught is equal to rho one x one square divided by two epsilon plus rho two x two square divided by two epsilon

So it is this one over two epsilon and rho one x one square plus rho two x two square the weight the depletion region width is x one plus x two that is the width of depletion region this is x 1 and this is x 2 and this is depletion region

So x is x 1 plus x 2 and then we have yet another relation row one x one is equal to rho two x two

So from these three equations eliminate x one and x two and see what happens

So from uh first thing i can rewrite this as v naught is equal to one over two epsilon and let me write in terms of ah row two

So rho one x one is same as rho two x two

So i am writing this term here and times x one and then i have rho two x two square it is this which is one over two epsilon and then you can take rho two common and x two common and it is x one plus x two and that is equal to one over two epsilon and then row 2 and x 2 and capital x

So this is 1 and then x 2 you can write in terms of x from here from these 2 you can write they are in inverse ratio

So x two will be equal to capital x times rho one divided by rho one plus rho two and x one which i do not need actually will be x rho two divided by rho one plus rho two

So if you add x two plus x one what you get is capital x which is here and if you multiply x two by rho two here and x 1 by rho 1 you get rho 1 x 1 equal to rho 2 x 2

So these are the relations

So let us come back here your v naught is now 1 over 2 epsilon and then row two and capital x it is here and then x two for x two you have to write this

So you have another capital x you have a row one and then divided by rho one plus rho two

So capital x square is equal to two times epsilon times v naught rho one plus rho two and that divided by rho one rho two and

So x is equal to square root of two times epsilon times v naught and one over rho one plus one over rho two

So this row one and rho two they are related to the concentrations of impurities that we have put in after all how that charge appears in the depletion region when you have a donor impurity it comes with one extra electron in the outer orbit but the whole thing is

neutral

So when this electron diffuses and goes to the other side what it leaves behind is a positive ion

So each donor impurity atom each donor impurity atom gives you one unit of charge positive charge and hence the density of charge will be e times the density of these donor impurity atoms in that region and hence that rover will be just e times that number density of impurity atoms and same thing happens for that acceptor impurities on the p side you put acceptor impurities and these acceptor impurities once again they come with one less electron in the outer orbit but it is neutral and

So when this hole migrates to the other side it leaves behind a negative ion and therefore the negative charge which is there in that region will be just e per acceptor impurity and hence the charge density will be e times the number density of the acceptor ions

So what you can write rho 1 is e times n a acceptor ions density and rho 2 is e n d donor iron density

So if you put it here you get this is square root of two epsilon over e v naught

So it is one over n a and plus one over n d

So that is the relation between depletion layer with and the potential barrier here

So if the potential barrier is high then the depletion width will be more if the potential barrier is low this will be thinner

So that is how these two are related and then it depends on the donor iron or acceptor ion densities also if the semiconductor is heavily doped

So that n a and d are large then this quantity will be small the depletion layer will be small and it is understandable if you have a large doping if the density is high you know the holes here and the electrons here if the density is too high only a small layer will be able to create a large amount of field ah because the charge densities will be large and therefore the depletion layer will be small

So it depends on the concentrations it depends on the on this width now how the current flows if there is a potential difference between the p side and n side is there a current if there is an electric field if there is a potential difference is there a current it cannot be unless i complete a circuit ok

So if i have this junction p n junction and what we are saying is the p side is at a lower potential and n side is at a higher potential ok we had calculated all those things quantitatively and we have this kind of potential diagram ok the energy diagram for electron is reverse but this is how

So this side is at a lower potential and this side is at a higher potential and the drop of potential is of course only on the depletion region after that the potential remains constant

So that means this is at a lower potential this is at a lower potential and this is at a higher potential now if i connect these two through some circuit if i connect this let us say i put a bulb here and connect it if there is a potential difference should there be a current like this and my bulb should glow it does not happen why because the junction when it is prepared for external connections you have to put some metallic contacts you have to put some metallic contact somewhere ok

So some metallic contacts you have to put

So that it can be joined to the external world and then just like you had different materials on this side and this side and it created a potential difference across that junction similarly you have different materials here on one side you have the semiconductor on the other side you have this metal

So there is a potential drop here also potential difference here also similarly there is a potential difference here also and when you combine all these things the three drops the drop across the junction the drop across the middle contact here metal and semiconductor that contact and here on the right side also you have another metal semiconductor contact

So when you combine all those things then the potential here and the potential here again turns out to be the same and no current flows but inside what happens inside this pn junction inside the semiconductor what happens you do have a potential barrier if you draw a potential energy diagram you have just a reflection of this upper one and it is of this kind

So this is the potential energy diagram now for electrons

So if you have electrons which are sitting here this is my n side remember

So i am talking of majority carriers now if my electrons are sitting here this is the conduction band energies if my electrons are sitting here and tries to come towards this p side it has to undergo the repulsion from this electric field and therefore they will be sent back into inside similarly if holes for holes the potential energy diagram will be reversed this this will be the potential energy diagram will be like this

So if holes try to come from left once again the electric field will push them back but then all the electrons are not at the bottom of the conduction energy band

So some electrons which are at a higher energies they will be able to cross this barrier

So the conduction electrons which have somewhat higher energy and why they have higher energy because of the thermal energies because of the temperature kt is the average exchange of energies and like that

So if it is higher the temperature there is a higher probability of populating the higher levels

So some electrons will always be there in the higher energies in the conduction band and they should be able to cross this barrier electric field will decelerate them ah will reduce their kinetic energy potential energy will increase but still they will be able to cross and

So the diffusion current is not exactly zero the if energy if these electrons are crossing that is creating a current in the opposite direction similarly some of the holes ah can really go from this p side to n side despite of this electric field which is repelling them which is decreasing this this motion

So you do have some kind of a diffusion current

So we call it diffusion eye diffusion diffusion current majority carriers try to diffuse on the other side because of that concentration gradient and facing the position of this depletion layer electric field still some are able to cross and that creates what we called diffusion current and this diffusion current is which side to which side it is from the direction is from p to n because these electrons which are trying to diffuse here

So that will create a current in this direction and then holes which are trying to diffuse on the n side that will also create a current in the same direction

So this is the diffusion current but how can there be a current if there is no current going in the circuit how can a current exist across the junction only

So the other part is in this depletion region you have electric field but you also have minority carriers you also have minority carriers although this is n type although there are large number of electrons here but there are some holes and similarly this is p type and for in this p type also there are some electrons these are minority carriers and for the minority carriers the electric field is all supportive if it is repelling electron it will attract hole if it is repelling whole it will support to this the opposite sign

So for the minority carriers this is not a barrier its rather electric field which encourages this kind of motion

So the minority carriers will go the electrons will go from this side to that side because of this electric field the holes will go from this side to that side because of the electric field electric field will support that and this current will be prompted by the electric field and this is known as drift current if there are generation of electron hole pair in the depletion region that will also be swept away the carriers will be swept away and will contribute to this drift current only in the same direction and the direction of drift current you can see from this diagram the holes are going from right to left

So giving a current in this direction and electrons are going from left to right again giving a current in this direction and this is your drift current

So the drift current and diffusion current are in opposite direction diffusion is because of the majority carriers concentration difference and the drift is because of the minority carriers because of the electric field existing and in equilibrium this diffusion current the magnitude is same as the drift current and hence net current is zero

So this is when we have not added any circuit we have not added any cell any battery any voltage source any resistance nothing this pn junction is just lying in the almera even then the diffusion current and this current are are going in different directions the activity is is on is not idle now the next task is what happens if we connect a battery to it we apply some voltage to it which is known as biasing ok

So let us say we have this p n junction and this p n junction the same this is p type

this is n type and of course depletion region and everything and the metallic contacts here metallic contacts here and we connect a cell to it and let us connect the cell in this fashion lets say some small voltage given here some some v is given here

So what happens when i connect this external battery here if you take this n type as the reference i am raising the potential of this p type by this v

So this potential which was of this type when there was a no battery connected this was v naught and that was v one and

So on this was the potential barrier in fact i do not need this line anymore when i connect this battery of potential difference v here and if i say that my this n side is grounded

So the change is here with respect to this n side this potential here is raised by this v and

So it will become this it will become this

So as a result this height this barrier height is now only this much this is a new barrier height the barrier height is reduced this is known as forward biasing biasing is when you externally you are trying to influence it you are biasing p region over n region or n region over p region

So that connecting this battery or connecting this voltage source is known as biasing and this type of biasing where the positive of battery is connected to the p type and negative is connected to the n type this is known as forward biasing and in this forward biasing what happens the barrier height the potential barrier height is decreased ok the potential barrier height is decreased and also the width of the depletion region also you remember that width was something like square root of 2 epsilon over e v naught one over capital n a plus one over capital n d

So if this barrier height is reduced depletion region width is also reduced

So one thing is that height is decreased and the second thing is that width is also reduced

So this width this depletion region which where the electric field exists that decreases the height decreases

So the majority carriers are more than happy because this they had to cross this displeasion region in which this electric field was existing now the depletion region is thinner and then the total energy difference that was there that they had to surmount that is also decreased and therefore what happens the diffusion current will increase does drift current also increase drift current was supported by this electric field

So whatever minority carrier wanted to come they were allowed to come

So even if this support if this attraction repulsion is increased that does not actually increase the drift current because the disc drift current is decided by the concentration of minority carriers how many minority carriers are there to take that support whereas for majority carrier it was different ah its not the concentration of methodic areas but it was going uphill

So the drift current which is decided by the concentration of minority carriers that is not changed because of this biasing of course if you increase the temperature then that minority carrier concentration will increase because no more because more whole electron pairs will be there and all those things

So for a given temperature this will increase whereas the drift current will remain the same

So the net current will increase in what fashion not linearly because it all depends what is the population of electrons in those higher levels and that is exponential that that has a more complicated form

So the current is first it increases very slowly and then after certain voltage it increases suddenly steeply

So this side is now this battery voltage v this v that we are putting that is now this side and this side is the current in this non-linear way it increases and the drift current is very very small and that is not affected by this and that drift current is going like this and remains the same

So we will stop here and we will take from this point only next lecture you