**Fundamentals of Semiconductor Devices**
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**Lecture – 16**
**p-n junction under equilibrium (contd.)**

Welcome back. So, if you remember in the last class we had discussed about the introduction of p-n junction. We have also discussed about the basics of how depletion region is formed, about the built in potential I told you how built in potential you know is dependent on doping. We have derived the expression for built in potential. And then I also told you that white band gap or smaller band gap materials will have different built in potentials. I told you that doping and depletion width are inversely proportional.

So, if p side are is very highly doped then depletion will be predominantly on the n side and vice versa so doping and thus because the aerial charge density has to be conserved. So, this is the some of the things that we are discussed in the last class. If you recall also I told you that depletion region that is formed will also sustain a field, there is no field and the neutral region away from depletion. So, all this things we have covered in the last class. And please remember that this p-n junction will be the building block for so many devices.

So, you know if you want to calibrate any practical device we want to understand how the blue led is a working which by the way is your white led now then you understand again p-n junction right. So, everything is p-n junction eventually. So, today in this lecture we shall first try to establish a relation between depletion width that forms of the junction and the built in potential ok. And we will derive the expression and that we will try to solve some numerical if time permits.

And then from next class we will perhaps study about p-n junction in non equilibrium; which means you apply a voltage, you apply a bias so current will flow. And that kind of a analysis we will do in the next class probability ok. So, today we will start about we will we will conclude p-n junction in equilibrium by establishing essentially the relation between built in potential and the your depletion width ok. So, let us come to white board now.

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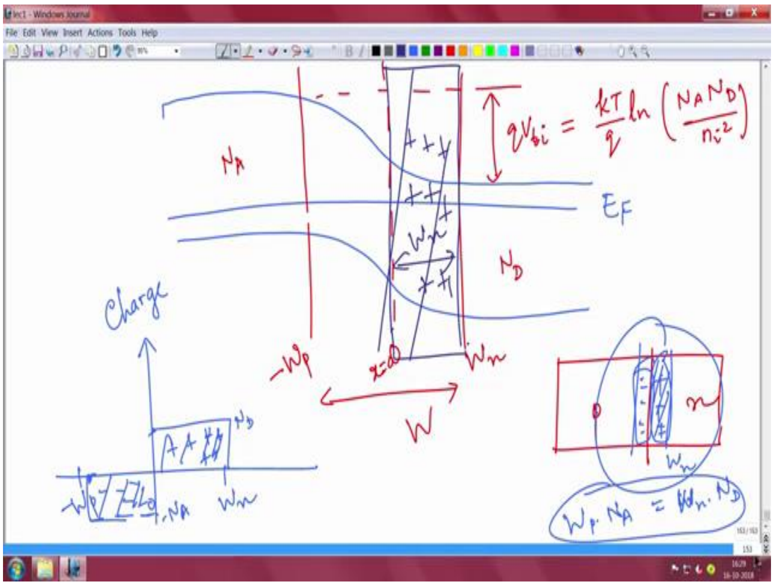


This is the you know so let us get in a new page here I will tell you again. So, if you recall this is a Fermi level right. And this is your conduction band, this is your valence band. So, I told you that this is your built in potential

$$qVbi = \frac{kT}{q}\ln(\frac{N_A N_D}{n_i^2})$$

This is your doping on the n side which is N D.

This is doping on the p side which is N A and n i is your intrinsic carrier concentration. So, this is the equation we can actually used to find out the built in potential. I told you the field is existing only in this region which is your depletion region. Suppose this was your actual junction at x equal to 0. So, depletion x tends to x equal to W n on the n side. And x equal to minus W p on the p side; I told you if the and here I am assuming that doping N A and N D are moderate and are similar you know.

If one side is very highly dope then the depletion will be only in the other side in likely dope side if you recall that ok. Because, this is your p this is your n some depletion forms here, some depletion forms here this areal density of this is W n right. So, W n times your the doping where is there N D in this should be equal to the areal density here that is equal to W p into N A.

That is why it comes the inverse proportionality if you recall. So now, if you draw the charge diagram of this of course, you know if you draw the charge then you will see that this is x equal to 0 this is x equal to W n this is x equal to minus W p. So, on the n side you have positive charge plus plus plus plus this is N D this value is N D. And the negative this side you have minus this value is minus N A so this is minus W p.

So, you have minus minus minus. So, the area under this and area under this has to be same that is what we have done it this. Let us focus on say this region; the depletion on the n side which width is W n. And this is filled up with positively charged ionized impurities right this whole thing. So, let us focus on that.

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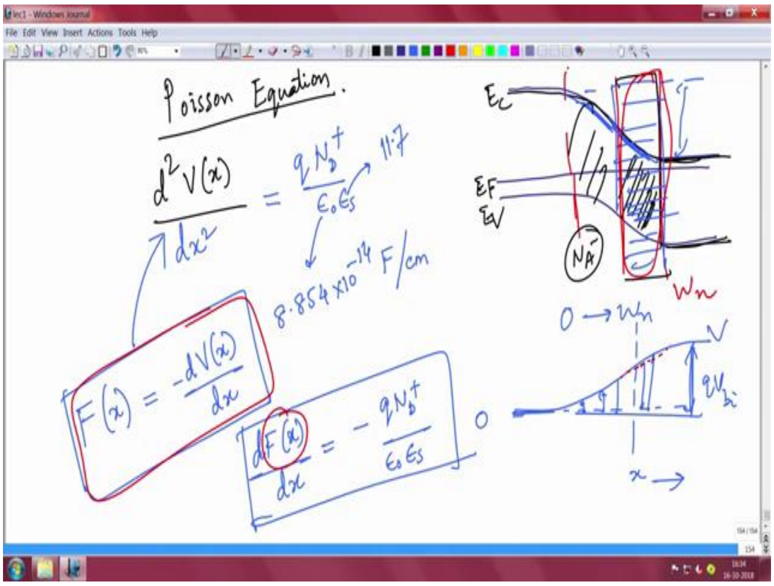


So, if I focus on that then I will draw it in a smaller scale. So, that we can good analysis also do the mathematics at the same time. So, this is the thing ok. So, I told you that this is your say junction x equal to 0. We are going to concentrate on this part which is x equal to 0 to x equal to W n. So, this is the depletion on the n side, the field exists in this region also the field exists in this region also until this region, but we will consider only this region the field exists here.

So, no field also there is no field in the neutral region which is this, which is this right this region there is no field ok. The field only exists in the depletion region. So now, you have to believe we have to understand that in this region we have only N $D^+$ as the background charge. Because mobile electrons have re combined with holes when they were forming the junction. So, only N D plus is the charge that remains here which are immobile.

Similarly N $A^-$ remains in this part, but we shall come to that later. And both N $A^+$ and N $D^+$ of to balance each other the areal density I just told you now. So, we will consider we will understand that in this area you know in this block essentially we only have N $D^€$. So, now, we shall write the Poisson equation. You remember the Poisson equation from your 10 plus 2. Poisson equation, thus come from Gauss law and if you recall is basically the second derivative of the voltage you know. This is electric conduction band, this is a valence band, this is Fermi level.

You remember that this is electron energy this entire band diagram is electron energy. So, this electron energy this whatever I am putting as E F E V this is electron energy actually is your q times potential energy please remember that ok. And there is negative sign of course, because charge is negative electron. So, this is essentially before I come to Poisson equation this is essentially energy band diagram for electron energy; the potentially look opposite to that the potential we will look somewhat in a mirror image.

So, it will look like the potentially we will essentially look like opposite. So, it will look like this which means this side is a higher potential. So, suppose this was 0 point and the if I take this reference as the 0 potential than this potential there is a potential drop that is changing as a function of x. Now there is a function of x the potential is changing you see this. That is total potential drop that is happened is actually qV bi that we know because that is only this.

Exists there is a mirror image because potentially is negative of the electron images negative of potential anyways. So, here we are talking about the potential. So, the second derivative of the potential is equal to total charge by $€_0$ $€_S$, $€_0$ is the dielectric constant of vacuum which is 8.854 into $10^{-14}$ farad per centimeter. This is your the free space dielectric constant and $€_S$ is the dielectric constant of the material.

For example in silicon this is 11.7; what is the charge I am talking about only this part as I as you recall I am only talking about between 0 to W n. The charge in this part is N $D^+$ I just told you now. So, I can replace this by q N $D^+$. Fine I can replace that as q N $D^+$ ok. Now, I have to solve this Poisson equation to essentially get v. But before that I can say that electric field and that might be a function of x also, you know there is as an electric field in this region; in this region there is a field because there is a slope.

There is also electric field here, there is also electric field here that is as a slope here. So, the electric field is nothing, but the negative of the gradient of potential energy if you recall right. So, I can plug this here and I can say that it actually is dF/dx is equal to -q $ND^+$/ $€_0$ $€_S$. Now you do a derivative into an integral equation. What are you trying to find out? We are trying to find out field F(x) in this region, this region. Once you find out the field you can find out the potential; once you find out the potential what will happen? You can find out at any point as far as a potential. So, it will also give you many ideas actually we will come to that.

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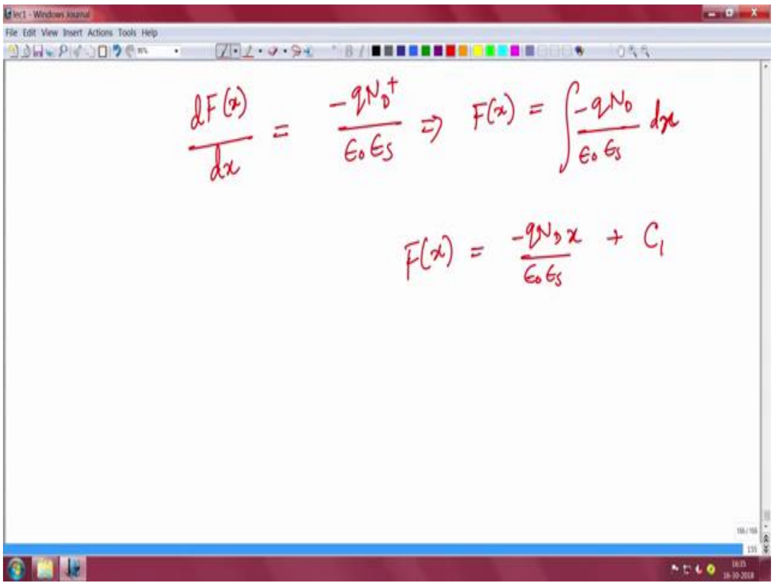


So, now we have to solve this equation dF/dx is equal to as q N $D^+$ /$€_0$ $€_S$ which means F(x) is equal to -q N $D^+$. I can write this is -q N D only because N $D^+$ and N D are same. There is 100 percent ionization you know €0 €S epsilon S into dx right into dx. So, I can see the field here. So, how will I do that now?

So, field will be now equal to minus q N D/ $€_0$ $€_S$ into x plus some constant right into x plus some constant. Or, I can just say you know I can just say this is x plus some constant C1. In the first boundary condition if you look here is that at this point let me rub little bit here.

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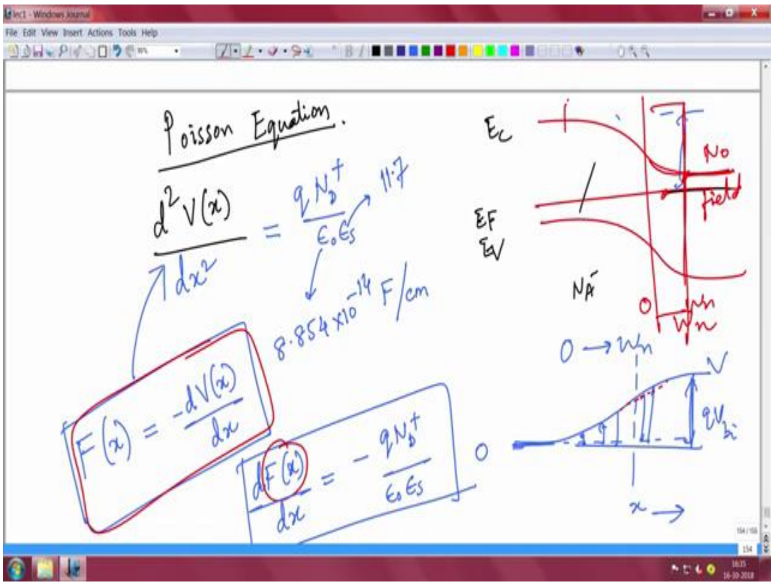


This is the Fermi level for example, this is the conduction band, this is the valence band. I am talking only of this part right only of 0 to W n at the end of W n here the field becomes flat after that there is no field; which means at x equal to W n. Your field vanishes because the field exists only here.

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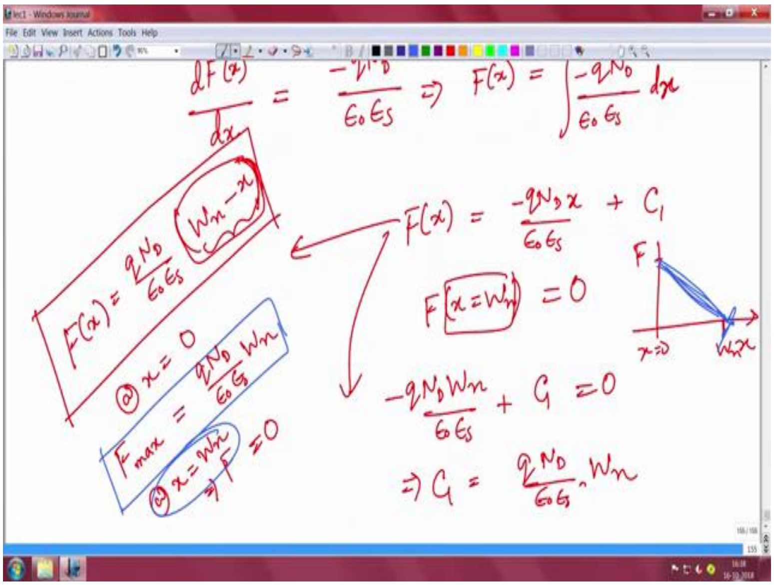

So, the first boundary condition is that F at x equal to W n will become 0. So, in this I will put F equal W n. So, it will become (-q N D W n )/ $€_0$ $€_S$ plus C1 is equal to 0 because at that at x equal to W n the field has become 0. So, C1 is equal to q N D/ $€_0$ $€_S$ into W n. So, I can write this as

$$F(x) = \frac{qN_D}{\epsilon_0 \epsilon_s}(W_n - x).$$

What does it mean? It means that a field is decreasing linearly at x equal to 0 the field is maximum. And the value is

$$\frac{qN_D}{\epsilon_0 \epsilon_s} W_n$$

this is the maximum value will have. As you keep increasing x this quantity will reduce your field will reduce. Eventually at x equal to W n your field will become 0.

So, field is decreasing linearly as x is increasing which means if I have plot field versus x and a W n the field become 0 at x equal to 0 the field is highest. So, it will become like that right the field will become like that. Accept that there is a small sign there has been an error I have put an error on the sign, but that is ok. I mean the magnitude is all the same actually you know the Poisson equation in the in solving the Poisson equation if you look here there should be a negative sign of the beginning actually.

So, that the negative will cancel of, but that the negative sign will actually not the magnitude will all the same the magnitude is all the same. So, this is your essentially the maximum field that you will get. And, the field will decrease linearly as you approach x equal to W n. So, this is your at the edge of the depletion your field will become it will become actually will finish it will it will vanish.

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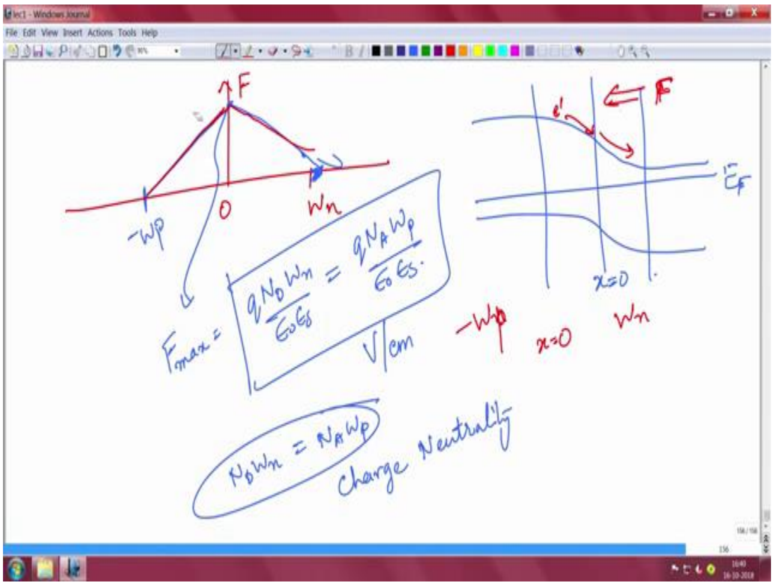


So, similarly I can do the same exercise for the p side if you recall this is E F this is this is this. I told you that I had only taken care of this is x equal to 0 and this is the depletion edge here. Only took this part side and the n side. But I can also take you know this is minus W n W p.

So, I can also take this part and the p side I can solve the same thing and I will get again a field profile that will look like field. So, this is x equal to 0 this is equal to W n. So, I told you the field you know is maximum here. I reduces to 0 here this x will W n it linearly decreases to 0. Similarly on the p side minus W p it will basically start from here the same value will be here and it will basically reduce to 0 here [FL]. So, this peak value I told you that peak value of field is q from the previous solution W n by $€_0$ $€_S$.

This is the same if you get from this side also from if you solve the p side we also get the same value which will be like q N A W p/ $€_0$ $€_S$ If you actually you know this is the same essentially the peak this is the peak field and this is an volt per centimeter. Of course, we can see that we can cancel out q epsilon. And now what will remain here is N D W n is N A W p which is basically the charge neutrality I have already told you with basically gives you the same charge neutrality equation that that areal charge density on this side and this side has to be same.

So, if you recall again I will rub it here. Let just make it let us make it this is the Fermi level here this is the conduction band this is the valence band. And now actually I have shifted the diagrams will make and draw again here. This is a Fermi level and then this is your conduction band your valence band this is your x equal to 0 point this is your n side this is your p side. I told you that an electron will roll on this side. So, it will go with that has the. So, the field is in the negative x direction. So, field will be negative x direction. So, the field is not the field is not exactly this is the value of the field by the way.

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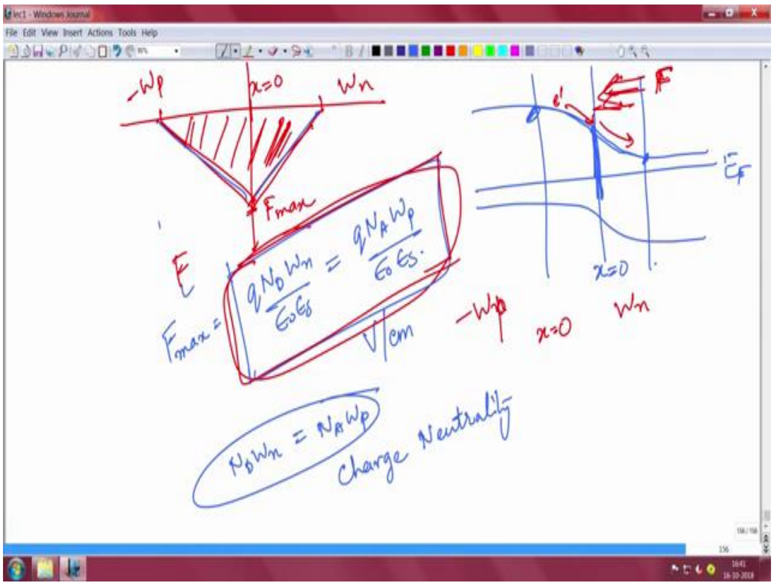


But, because field is negative x direction the field will you know essentially look this is x equal to 0. And plotting the field here is x equal to W n this x equal to now as W p. This is the maximum field and field will look actually like this I mean instead of positive it is basically negative everything else is same the value and everything is same. The field is actually in the negative side.

And the reason this is actually negative, but the reason I got it positive as I mentioned is because I missed out a negative sign here in the a Poisson equation here. So, that negative sign actually does not change anything except the direction. so basically what is happening is that the field is essentially in your negative direction. So, that is why I am giving it is negative here. But the magnitude and the value is that the way it is decreasing and all everything is the same.

Just the next to negative sign that you know I have missed out. So, this is your field on both side and it is linearly; it is linearly decreasing from the x equal to 0 point to this side. You know an x equal to 0 to this side right. So, essentially at this midpoint the field is maximum the field decreases gradually in linear array and it becomes 0 here. The field decreases gradually linear way and it becomes decrease here. Now if you recall the expression for field if you recall expression for field.

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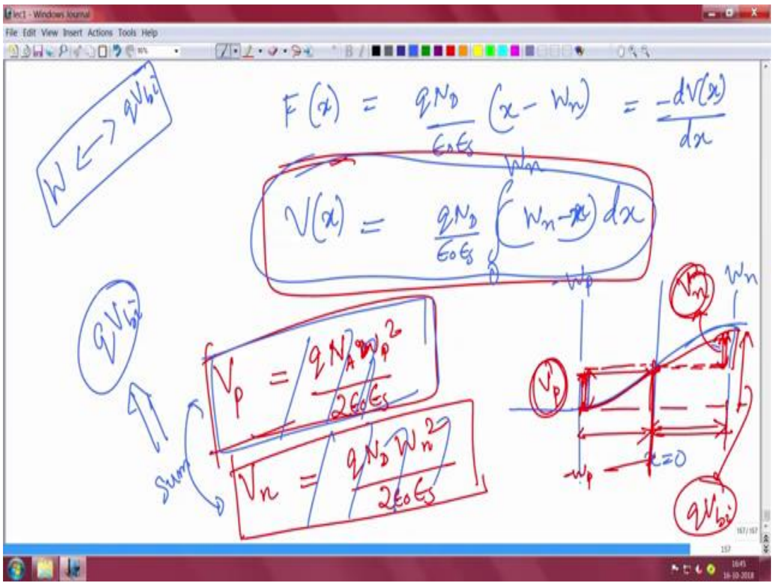


Now, I will put the correct expression F(x) is equal to

$$F(x) = \frac{qN_D}{\epsilon_0 \epsilon_s}(x - W_n)$$

this is the true field expression Now this is actually minus dVx by dx. So, I will write down you know the I can solve it again. Now so it will be V of x will be equal to q N D/ €0 €S negative sign is there.

So, I will make it W n minus x dx. So, now, I can solve it there will be limit you know what is happening is there I told you the potential goes like this you know. So, this is your x equal to 0 point this is your x equal to W n point this is your x equal to minus W p point the potential is changing. And your net potential drop of course, has to be a built in potential qV bi which we have this already derived.

So, you see your this part is your depletion on the n side this part is your depletion on the p side. So, you know this is the potential drop that is happening on the p side and this is the potential that drop that is happening on the n side remember. So, the total of the potential drop will be the built in potential. So, the potential this is dropping on the p side

I will say this is Vp this potential drop. And the potential that is dropping on the n side with respect to the x equal to 0 point this I will say as V n.

So, this total this potential drop on this side and potential drop on this side will add up to the total built in potential ok. We will add up to total built in potential [FL]. So, now this you know value solve you can put that limit that you know I am integrating from x equal to minus W p to I m integrating to this point. Then on the n side I am integrating from x equal to 0 it x equal to W n.

The unknown quantities will be V p and V n because that is the total potential drop that I am having, but eventually when you do the simplify the math and everything will be uploaded is notes. So, there is no point, but once you do that you will see that the potential that you are dropping on the p side V p is actually q N A W p square W p is the depletion here by 2 €0 €S.

And the potential that you are dropping on the n side is q N D W n square this is the distances you know by 2 €0 €S. So, these are the potential that is dropping on either side of the depletion and the total summation of these two if you summed is up to both of them then that should give you qV bi. So, that is the potential that is dropping across each of the side of the depletion region good. So, now what should you do now?

So, now, we have to still we I told you we have to establish a relation between the total depletion width and built in potential total depletion width and built in potential we need to establish relation. Till now we have gotten the built in potential and both side right on either of the side. And how did you get that we got that the solving this equation. We solve this equation you can actually this you see this is an x here.

So, it will be x square term and then I told you can set the limit from x equal to minus W p to x equal to 0 ok. And that will give you the total voltage drop V p similarly we will get from here to there you can set the limits here. So, if you do it for the n side it will be from 0 to W n you can exactly calculate that is your V n you will get this value for p type you will get this value and. So, you are those up and you will get kV bi now.

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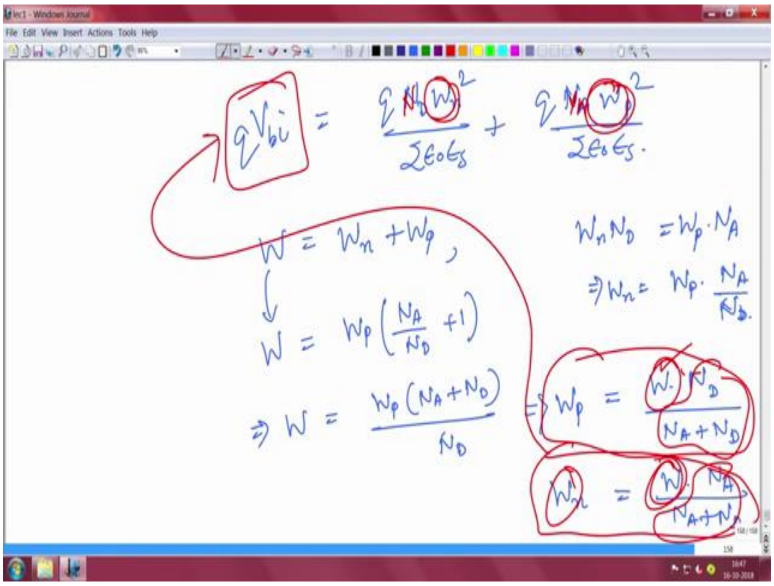


So, I will write it as qV bi is equal to q N D W n square by 2 €0 €S plus q and N A W p square by 2 €0 €S. Now you also recall that W is equal to W n plus W p because there is a total depletion with you also recall that W n times N D will be equal to W p times N A that you know the areal density on both side the same here.

So, I here I can say that W n as actually equal to W p into N A by N D. From here I can say the total depletion width is equal to W n which is W p N A by N D plus 1. So, I can say W is equal to W p (N A + N D)/ N D. So, you know I can say W p is equal to W into total depletion width into N D (N A + N D) similarly i can say W n is equal to W the total depletion width into N A (N A +N D).

So, I can put this value and I can put this value both of them into this expression. I can put them into the expression what will happen them I am substituting for W n in the as a function of W and these are doping of course. Similarly I am substituting the value of W p and W n as a function of W. If I do that then the on the left hand side I have built in voltage on the right hand side I have of course I have doping N A ND. And now epsilon, but there is no W p and W n everything is expression comes up W. Then I can express and relation if you simplify the out this is basically mathematical simplification.

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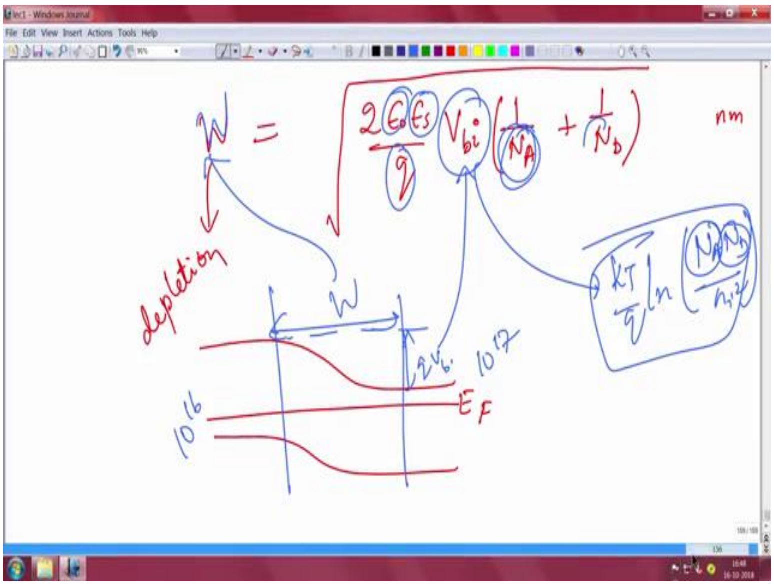


You will get an expression for W and that will look like

$$W = \sqrt{\frac{2\epsilon_0 \epsilon_S Vbi}{q}\left(\frac{1}{N_A} - \frac{1}{N_D}\right)}$$

And this is a nanometer or centimeter whatever. So, this is your depletion width the total and this you get from simplifying the above expression.

This is your total depletion width you know I will let me draw a p n junction again this is your Fermi level this is your conduction band. This is your valence band your this depletion your this built in voltage qV bi which is this sorry which is sign of this which is your this is connected to the depletion you know the depletion is this right is connected to depletion by this relation.

So, if you know the doping say one side doping is $10^{17}$ the other side doping is $10^{16}$ you know this doping you plug in the value €0 €S you know epsilon as for silicon is 11.7 or the material that is given you will find out q is the charge of electron. Built in potential is found out by

$$qVbi = \frac{kT}{q}\ln(\frac{N_A N_D}{n_i^2})$$

Once you know the doping of course, you can find out the built in potential. Then everything is known you can find out the depletion width right. So, if you recall I had given an example you know where if you slides back if you remember I had solve the problem few slides back I am not able to recover where I solve the numerical yeah it is here.

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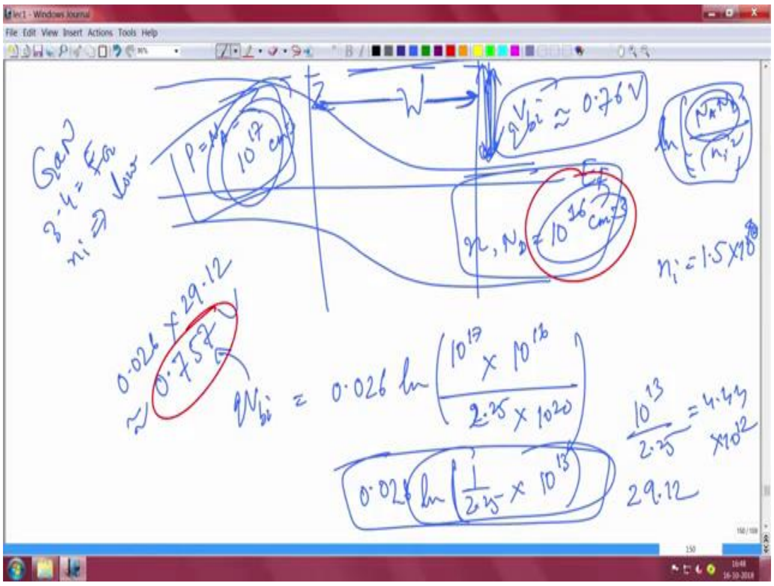

You know I solve the numerical and the p side is you know $10^{17}$ dope. And the n side is $10^{16}$ dope and the built in potential came out to be 0.76 volt. So, if I take the same expression here right. If I take the same expression here now and I try to do the depletion widths so you know what I will basically take the same thing.

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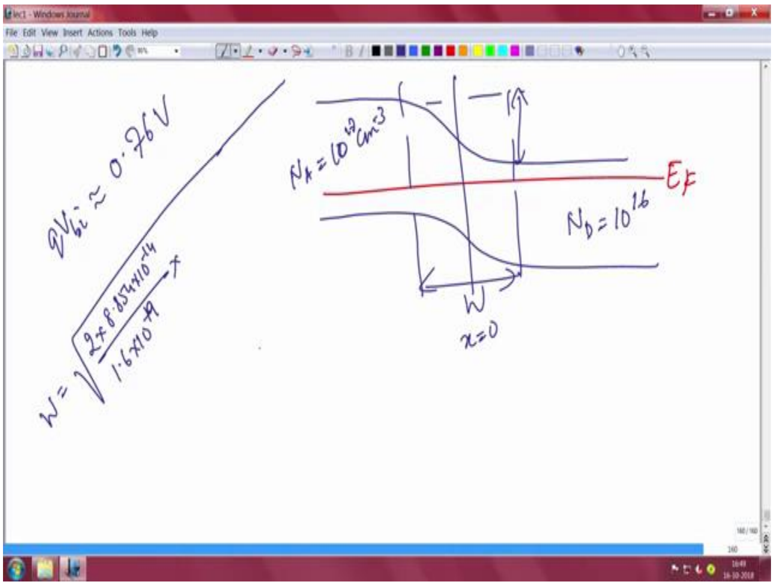


So, this is your Fermi level, conduction band, valence band, this is your x equal to 0. You know this is your depletion this is your built in potential. This is n type doping is $10^{16}$ p type doping is say $10^{17}$ per centimeter cube.

It is always in per unit volume of course. So, then you are built in potential it came out to be around 0.76 volt. So, then you for finding out what is the depletion this total depletion W you just have to do W equal to square root 2 into epsilon which is $8.84 \times 10^{-14}$ farad per centimeter you should be very careful about the units.

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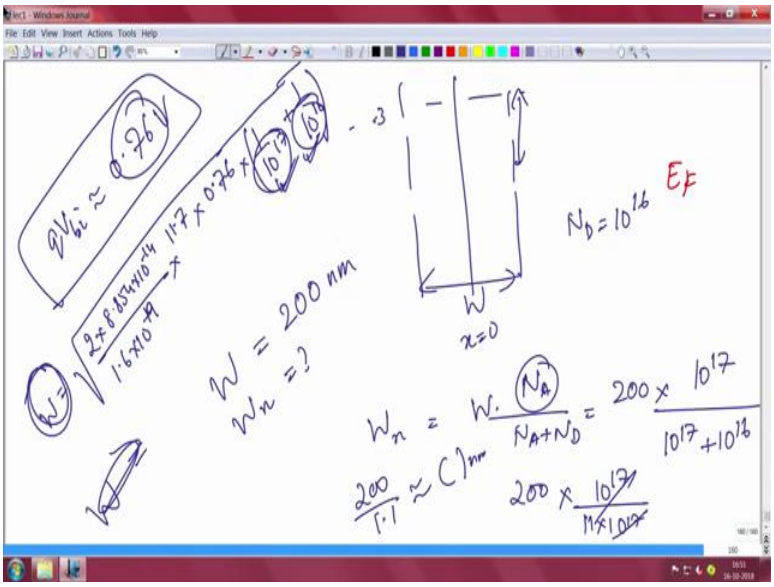

Divided by q which is 1.6x $10^{-19}$ column into your epsilon of silicon is 11.7 into built in voltage qVbi which is 0.76. This into 1 by doping 1 by $10^{17}$ by 1 by $10^{16}$; so, if you do this you will find out the value of W. And it can be few 100 nanometer it depends on whatever right.

So, of course, as a doping is lighter you know your depression weight is larger if your doping is narrow a very higher than a depletion weight is narrower ok. And your built in potential is higher right. So, this is what it now once you know the depletion once you know the depletion the, suppose the depletion comes up to a 200 nanometer. I am just giving an example.

Then how you will find out the depletion and n side oh that you find out by this relation right this relation which is depletion on the n side is total depletion into N A N A plus N D. So, this is 200 nanometer then it will be 200 is total depletion doping on p size $10^{17}$ and this will be $10^{17}$ plus $10^{16}$. So, you find out this will be 200 into $10^{17}$ by 11 into 10 to the power 6 1.1 into $10^{17}$.

So, this will be 200 by 1.1 that whatever that value is will be that nanometer depletion the n side. So, I told you if the p type is ten times higher doping then the depletion on the n side will be 10 times higher that is how basically it means. So, we have now understood the potential on the both side you know how does the potential dropping in total voltage we have related to the depletion width.

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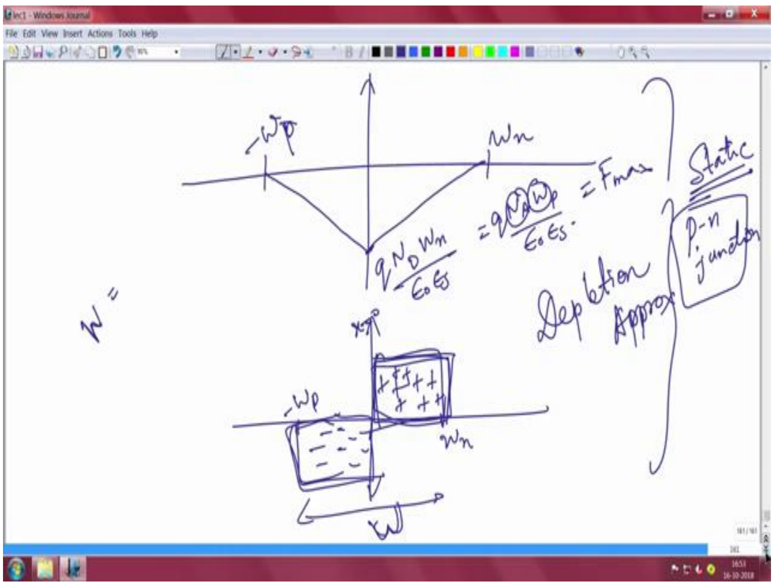

And I told you that your field electric field if you recall this is W n this is minus W p the field actually is maximum here and goes like that this maximum field is remember q N D W n / €0 €S which is also equal to q N A W p /€0 €S.

And the whole analysis that you have done till now assumes complete depletion approximation which means this is x equal to 0. For example, if I draw the charge on W n you have positively charged ionized course and on the other side you have minus W p. So, you have negatively charged acceptor ions. The assumption the depletion of approximation the depletion approximation tells us that you know there is absolutely no mobile carrier within this and within this.

So, this is a total depletion. So, there is absolutely no mobile carrier here everything is ionized a mobile charges when you solve the Poisson equation here. We get the field as we have discussed we also get a potential profile. So, we are good to setup the you know the field and the potential energy profile. So, now you basically know the static conditions. there will be many numerical problems to find out.

For example, what is the maximum field values will be given to you what is the depletion width W again value is will be given to you. Or, you know you are given that the depletion width, but you are not given the doping and vice versa. So, there will be and there could be many numerical problems that you know you have to solve. So, this is about basically about whatever we have learnt till now is about p-n junction in equilibrium or static conditions there is no voltage applied there is essentially no bias no light shining.

So, essentially is p-n junction in equilibrium there is no current flowing that is absolutely no current flowing. So, that is good now we are good to move ahead with the next concept here. We will go to p-n junction and bias, but before that let us stop for a minute and think about it you know realistically about different kind of semiconductors.

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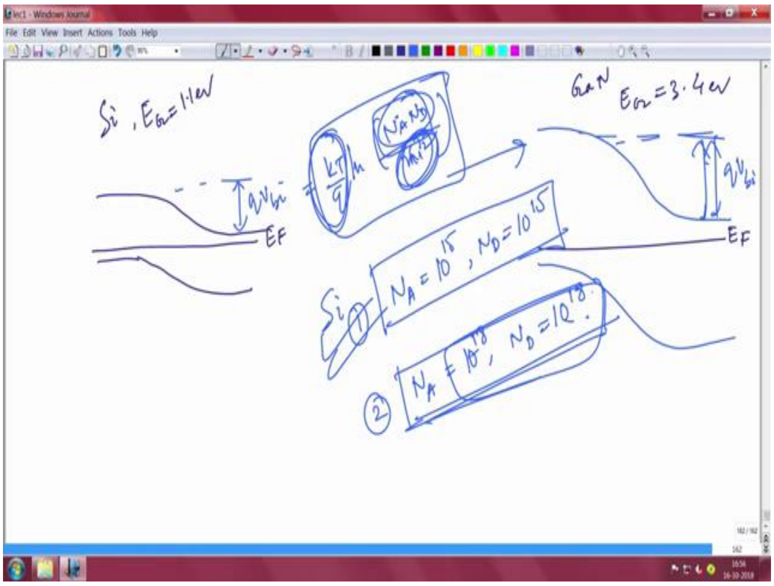


So, I told you that if you have say silicon the band gap is 1.1 E V suppose you have gallium nitride this is the another semiconductor whose band gap is 3.4 E V. So, silicon this is p-n junction right. So, this is Fermi level and this is your p-n junction like this sorry your p-n junction like this ok. So, gallium nitride the band gap is large so band gap is large so you know like that.

So, of course, the built in potential qV bi qV bi I had mentioned it is equal to k t by q l n of N A N D by $ni^2$. So, if you are this doping is same then ni for gallium nitrate is much slower. So, that is why your built in potential this is much higher. This built in potential scales roughly has the band gap. So, if you are band gap is large then the build in potential also will be large please keep there in mind. And that is very important as you also you can look at the, that are dependence on temperature.

If you increase the temperature what will happen because this will, if you increase the temperature in there this will increase. And ni square also we will actually increase with temperature. So, this will blow up which means the overall quantity we will have to shrink all right. So, there many things like this that we have to be careful about while you do device problems. And also there could be another thing is that when you increase the topic what happens. Suppose I take only silicon I have a I have 2 silicon p-n junctions.

A sample 1 has n p type doping as $10^{15}$ n type doping also is $10^{15}$ say sane type. I have a sample 2 where p type doping is $10^{18}$. And n type doping also is $10^{18}$ which is very high both of them are equal, but there very very high doping here and this very light doping here. So, what will happen now?

The built in potential for this sample will be much lower because your N A N D product is much lower the built in potential here will be much higher compared to that a much higher is than like higher because your product is higher right. Now, which will you know what is the limit to having a what is the largest built in potential one can have.

The largest built in potential one can have is the band gap of the semiconductor right. So, no matter how you dope you cannot exceed the band gap the semiconductor right. Because you know if you look at the band diagram of p-n junction again right.

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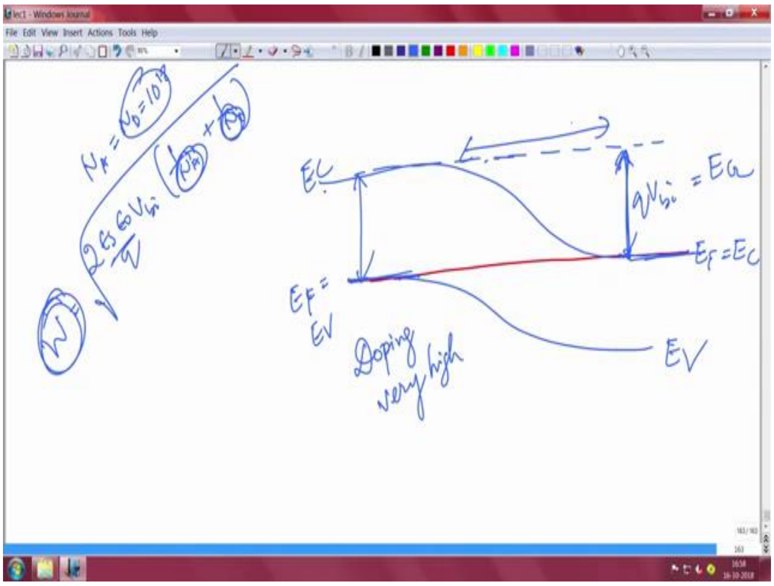

So, this is your suppose Fermi level and this is your conduction band this is a valence band. This maximum that you can get is actually the band gap and you will get that when you know when you have such high doping that your Fermi level on both sides touch the valence and conduction band. Suppose you know this is a valence band, but the Fermi level is on the p type and the p side of Fermi level it.

So, highly the Fermi is touching almost the valence band. Similarly, on the n side Fermi level is touching this is Fermi level which is also touching the conduction band on this side the Fermi level is also touching the valence band on the p side. On the n side Fermi level also touching the conduction band and then it is going like this right. This is the largest then built in potential you can have you see.

The built in potential is equal to band gap because this value is actually this value which is the band gap because this is your EC this is your EV. So, in the limit that they have Fermi level is touching the conduction band the Fermi level is touching the valence band which means the doping is super high very high. In that limit your built in potential will be equal to the band gap. Of course, when you are doping is very high if you are doping is super high N A and N D are $10^{18}$ right.

Then you remember the depletion width

$$W = \sqrt{\frac{2\,\epsilon_0 \epsilon_s\, Vbi}{q}\left(\frac{1}{N_A} - \frac{1}{N_D}\right)}$$

If this N A and N D is $10^{15}$ then this is very large. If this N A and N D are $10^{10}$ then this will be very narrow which means this depletion will be very narrow so it will be very sharp. So, actually how it will look like you know it will be very narrow junction. Because that the depletion will be very very low because your doping is very high. So, you are built in potential and your depletion go inversely as the doping you know.

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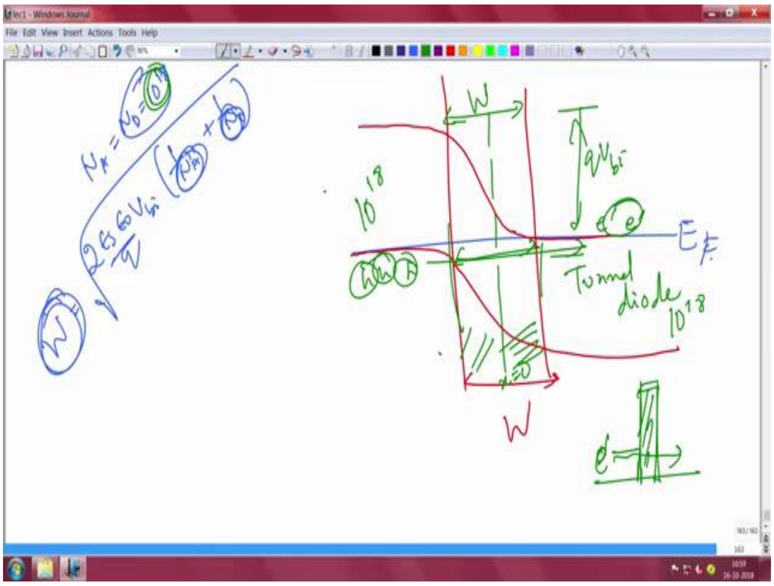

So, what will happen is that if this is your Fermi level. Then you are conduction band valence it will be very sharp depletion like this. It will have a very sharp depletion like the depletion; this is the depletion the total depletion is this. The total depletion is this is your x equal to 0 because the doping on both side is same $10^{18}$ $10^{18}$ it will be the same doping on both same depletion on both side.

But it will be very narrow it can be even 10 nanometer 20 nanometer or so on. There is a lot of holes there is lot of electrons. If this is very you know narrow then this depletion I am essentially is very very narrow. So, electrons and holes can even tunnel that will come later it was tunnel diode we can make you know tunneling diode you can make because it is very narrow.

So, electrons and holes can tunnel if you do not know what is tunnel; you know this is a quantum mechanical process where you know you know electron can or hole can for example, move across a barrier unlike in real life. So, if you have a wall; if you have a wall then you know if you have a ball it will not be able to cross the wall, but in quantum mechanics electrons and electron may be able to cross the wall actually.

When I say wall is not the wall made of breaker stone this is the wall of potential energy. But let us not talk about that. So, anyways the depletion will be very narrow if you are doping is very high. So, this is $10^{18}$ this is $10^{18}$ doping is very high. The depletion is very narrow in the largest built in potential you can have is the band gap beyond that you know it is this.

Now depletion when it will be it this is the largest depletion region you can have basically. So, we shall end the class today we have finished up static conditions of p-n junction. We have started with you know the relation between the Poisson equation and try to establish the relation between the field, the depletion region, the depletion region, and the built in potential.

Then where is the maximum field the potential drop on each side. It is all some numerical some simple examples, but there can be variety of numericals different parameters can be given you know because, we have established there mathematical relation between the depletion width and the built in potential with higher doping depletion width will come down and built in potential will go up please remember that.

So, static conditions of p-n junctions are now thorough we have now full control on that. What we will do in the next class is we will start with application of bias. Once we apply a voltage to p-n junction what will happen right what will happen current will flow. How do you understand that current flow now that will take some time. So, we will start there from the next class.

Thank you.