Electronic Materials, Devices and Fabrications
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Module - 01
Lecture - 10
Pn junctions in equilibrium

Let us start with the brief review of last class. Last class we started looking at junctions.

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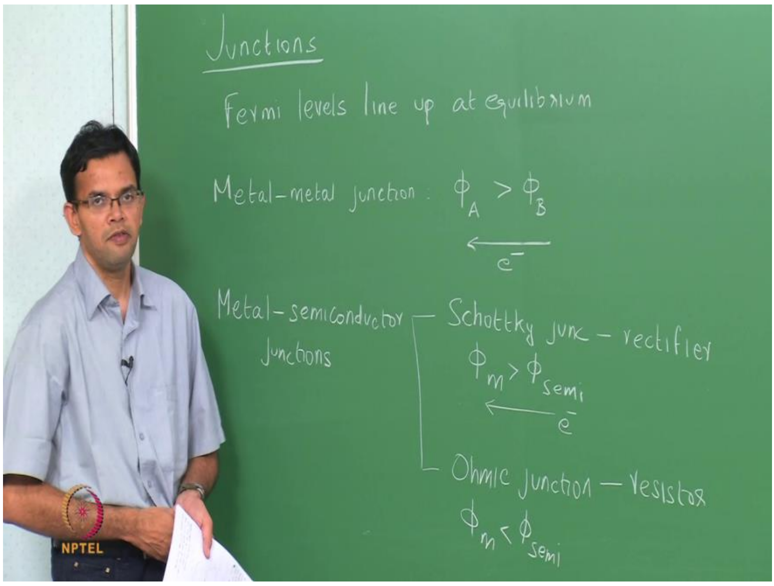

Junctions

Fermi levels line up at equilibrium

Metal-metal junction : $\phi_A > \phi_B$

$\xleftarrow[e^-]{}$

Metal-semiconductor junctions — Schottky junc - rectifier

$\phi_m > \phi_{semi}$

$\xleftarrow[e^-]{}$

— Ohmic junction — resistor

$\phi_m < \phi_{semi}$

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These junctions can be found between 2 semi conductors, on between a metal and a semi conductor or between 2 metals. We were in concern about how we will found the junction we just assume that we have an ideal junction or an ideal interface between the 2 materials with no defects. Whenever, we have a junction a junction is an equilibrium we said the Fermi levels must line up.

So, the Fermi levels line up at equilibrium and equilibrium is defined as when we have no external potential applied to the system. We first looked at a metal-metal junction so, we have 2 metals: A and B with work function phi A and phi B and we also said that the phi A is greater than phi B. In such a case we found out that electrons will move from B to A and this will create a contact potential.

We then, looked an metal semi conductor junctions and we saw that, they were 2 types: the first 1 is called the Schottky junction. So, this junction where the work function of the metal we call it phi m is greater than the work function of a semi conductor. In such a case, we found that electrons will travel from the semi conductor to the metal and this will again create a depletion region in the semi conductor and a contact potential.

We also looked at this Schottky junction under bias and found that it behaves as a rectifier. So, that in the case of forward bias the junction will conduct, but when we apply a reverse bias there is a small saturation current, but, the junction does not conduct. The other type of junction that we saw was the Ohmic junction in this case the work function of the metal is smaller than that of the semi conductor.

So, that you have electrons flowing the other way and the Ohmic junction behaves as a resistor. This is way we left off from last class; today we are going to look a junction between 2 semi conductors. So, we are going to start with a P-n junction.

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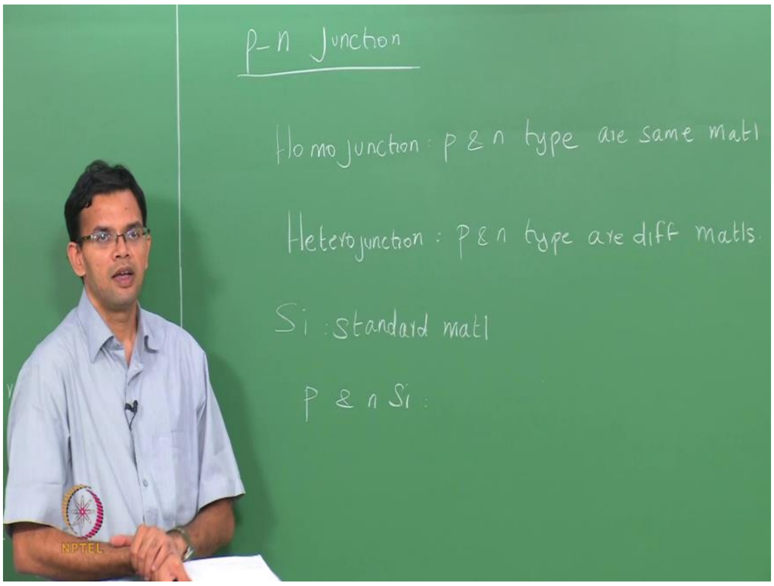

p-n Junction

Homo junction: p & n type are same matl

Heterojunction: p & n type are diff matls.

Si: standard matl

p & n Si:

As the name implies a p-n junction is form between an p type semi conductor and an n type semi conductor. Usually both are formed from the same material and such a kind of junction is called Homo junction. These are were both your p and n type are from the same material. We can also have a junction found, between different materials and such a type of junction is called Hetero junction.

So, in this case p and n are different materials we will mostly look at Homo junctions were they are the same material. Then, we will develop concepts of the junction in equilibrium and under bias and also calculations for the current and towards the end we will also look at the affect of having in different materials.

So, will find that hetero junctions have some really interesting properties and later, when we talk about optical devices as well like, LEDs or lasers will find that Hetero junctions have some advantage there. Homo junctions are easier to grow because, you are essentially the same material all you are doing is doping 1 side p type and the other side n type.

So, the interfaces are easier to found in the case of Hetero junctions the materials has to be chosen carefully so that, we have a good interface with no defects. So, those posses some restrictions in the kind of junctions there formed. But for the analysis we are going to do now, we going to assume that we have an ideal junction that is there are no defects. Most of the time we will talk about these p-n junctions with respect to silicon so, silicon is our standard material of choice.

But we will also look, at some examples of other materials and when we come to hetero junctions will talk a lot about compound semi conductors. So let us, consider a junction form between p and n silicon. So, let me start by drawing the band diagram for p type and n type silicon. So, I will first put them for a part and then bring them together to form a junction.

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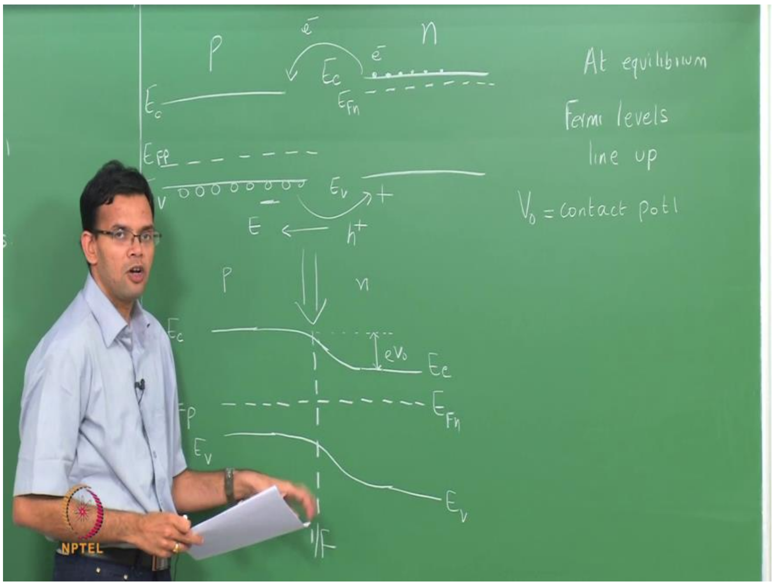

So, here is the band diagram for p silicon we have a conduction band Ec, valence band Ev. So, Ec is the bottom of the conduction band; Ev is the top of the valence band. The material is p type so; we know that the Fermi level lies closer to the valence band. Let me, put the Fermi level closer to the valence band and call it EFp. Now, I have n type silicon once again I have Ec Ev and then EFn.

So, the position of Ec and Ev does not change because both of them correspond to silicon so, the band gap is maintained the only difference is where we placed the Fermi level. So, we bring this p and n material together in order to form your p-n junction. And he said the first rule, is that an equilibrium the Fermi levels must line up. Another way of thinking about it is that in the n side you have excess electrons in the conduction band.

These electrons can move to the p side, on the p side you have excess wholes these are in the valence band and these holes can be moved to n side electrons moving here, holes moving the other way. Because, we have electrons moving will have net positive charge on the n side because, we have holes moving will have net negative charge on the p side. So, once again will have contact potential between the p-n junction.

So, let me draw the junction in equilibrium the first thing i will do is line up the Fermi level. Let me, mark the interface region so, this I call IF so, IF represents the interface between the p and n. So, far away from the junction the material behaves as a p or an n type. So, far away from the junction I have a p and in have n now we said the electrons move from the n to p.

So, that we have net positive charge on the n side and net negative charge on the p side which means, there is an electric field. The electric field goes from positive to negative in last class we also saw, that whenever we have an electric feel we have band bending and the bands bend in the direction of fields. So, the bands bend up in the direction of e. So, we have the bands bending on the n side up, we have bands bending on the p side down.

So, that is how the junctions found we can do the same for the band. So, this is my conduction band Ec, this is my band Ev and I have a contact potential at the junction. We V0 represents the contact junction so, we can draw a simplify picture of this.

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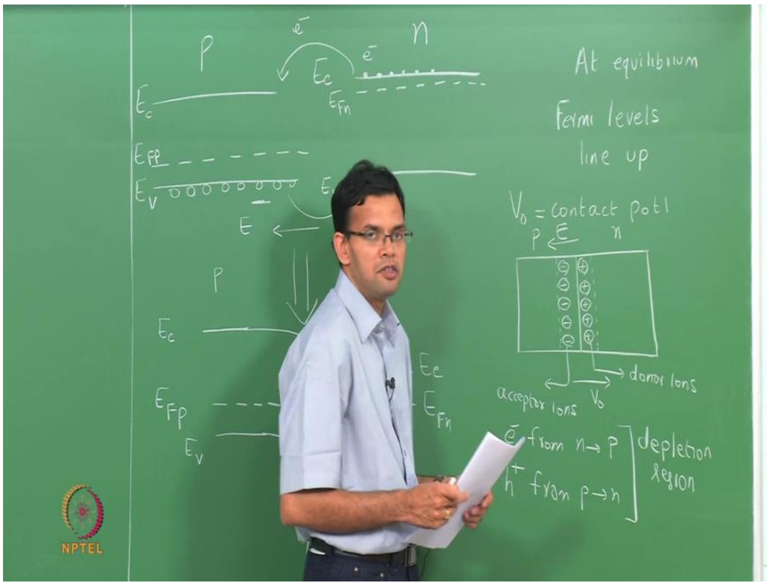

So, let me just draw schematic so this is my p side that is my n side I form my p-n junction electrons moved from the end to the p. So, when these electrons move you are left with donor ions since donor ions donate the electrons and when these electrons move they have a net positive charge. So, there is a net positive charge on the n side so, this net positive charge refers to the donor irons.

Similarly, there is net negative charge on the p side because, the electrons the wholes from the p side moved to the n side leaving behind your accepted ions and the accepted ions are negative. Which means, you have an electric field E and built in potential V0 so, we have excess electrons from n to p, we have excess whole moving from p to n. And when these meet they recombine and get destroyed.

So, what you are left behind is a depletion region around the junction. So, let me redraw this diagram and mark the depletion region. So, we are forming a p-n junction.

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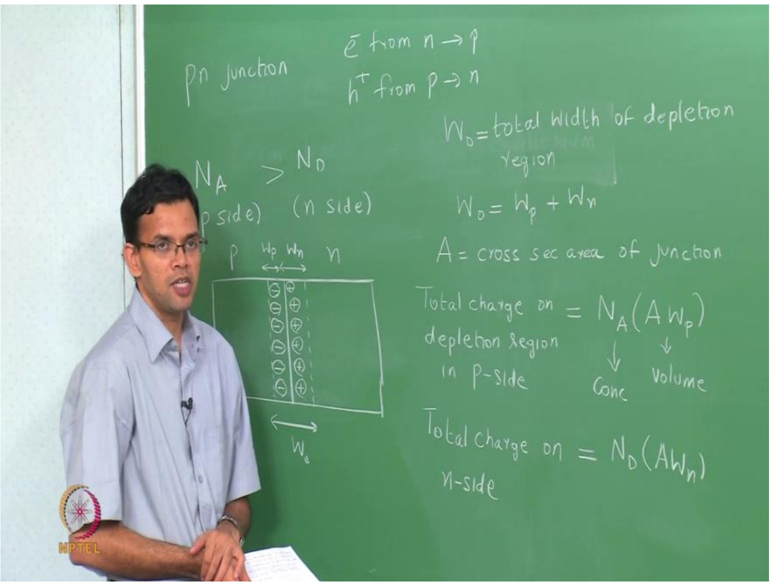

So, in the case of a p-n junction we said that we have excess electrons on the n side moved to p. We can think of this in terms of diffusion, where diffusion usually occurs from a higher concentration gradient to a lower gradient. So, the higher concentration electrons are on the n side and this moved into p. Similarly, we have wholes which move from p side to the n side and when these meet they recombine and form depletion region.

So, let us consider a p-n junction where the accepted concept concentration NA this is on the p side is greater than the donor concentration ND and this is on the n side. So, let me redraw my p-n junction this is the p that is the n there is a depletion region that is found because of the diffusion of the carriers we called this W0. So, W0 is a total with of the depletion region.

So, this forms at the interface of the p-n junction and extend to both the p and the n side. So, we have sum with on the p side let me call it Wp sum with on the n side Wn. So, that W0 is sum of the depletion region in the p side and the depletion region on the n side. So, we said that in the case of p-n junction we have net positive charge on the n side. Because, the electrons are gone leaving behind positively charge donors and u have a net negative charge on the p side.

Because, the wholes are gone leaving behind the acceptor irons. So, A is cross section of the junctions so, A is the cross sectional area of the junction we must have a balance of between the p and n side. So, the total charge on the depletion region in the p side is nothing, but the concentration of the acceptor irons times the volume. The volume is A times WT so this is the concentration, this is the volume.

We can similarly, calculate the total charge on the n side which is end the concentration of the donor ions times the volume Awn. In order to maintain the neutrality of charge this total positive charge must be equal to the total negative charge. So, let me equate these 2 and write the expression.

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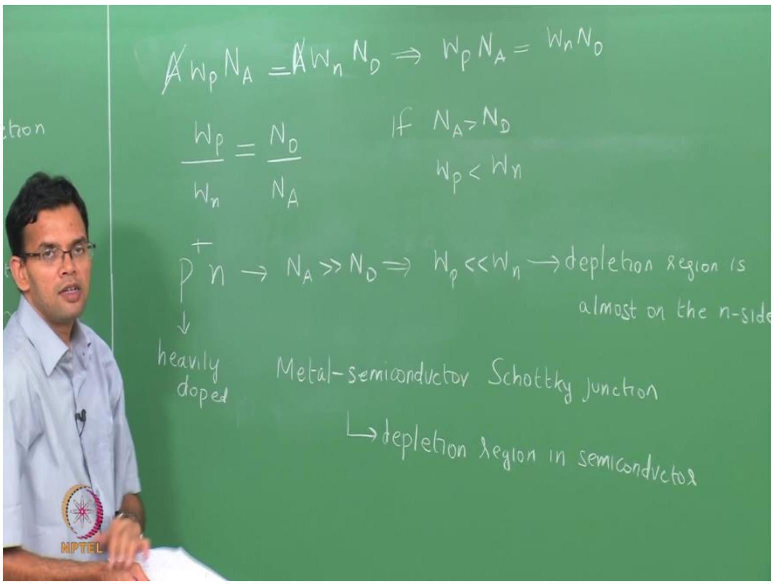

$\cancel{A} W_p N_A = \cancel{A} W_n N_D \Rightarrow W_p N_A = W_n N_D$

$\frac{W_p}{W_n} = \frac{N_D}{N_A}$

if $N_A > N_D$

$W_p < W_n$

$p^+ n \rightarrow N_A >> N_D \Rightarrow W_p << W_n \rightarrow$ depletion region is almost on the n-side

$\downarrow$ heavily doped

Metal-semiconductor Schottky junction

↳ depletion region in semiconductor

So, if you want to maintain charge neutrality you have A Wp NA which is the total negative charge on the p side must be A Wn ND the cross section area is the same. So, that can be removed. So, what we are left with is Wp and A is equal to Wn ND. The other way of writing this is that Wp or Wn is equal to ND over NA. So, the ratio of the depletion region on the p and n side is inversely proportional to the concentration of the donors whether, they are donors or acceptors.

So, if NA is greater than ND so, NA is greater which means, Wp will be less than Wn. So, the depletion region is larger than the e side than p side. There are certain p-n junctions that are formed between the heavily doped p plus region and n region. So, p plus refers to heavily doped region in this particular case, NA is usually much larger than ND.

So, using this above charge neutrality expression you have Wp is much smaller than Wn. So, that the depletion region is almost entirely on the n side and extreme example of this in the case your metal semi conductor Schottky junction. We saw this last class, where we found the junction between the metal and semi conductor and we have electron moving to the metal.

So, that we had the depletion region and the depletion region is almost entirely on semi conductor. And this is again because, if we try to look at expression similar to here, the charge density in the case of metal is much higher than the semi conductor. So, in order to maintain charge neutrality we have electron coming, not only from surface of the semi conductor.

But also from the bulk creating a depletion region and this depletion region lies entirely in the semi conductor side. So, the next thing to do calculate the built in potential comes between the p that forms we have p-n junction. So, we want calculate contact potential that form in p-n junction to do that. Let me; first draw how the career concentration that is whole concentration changes and the electron concentration as we go from 1 and to the other.

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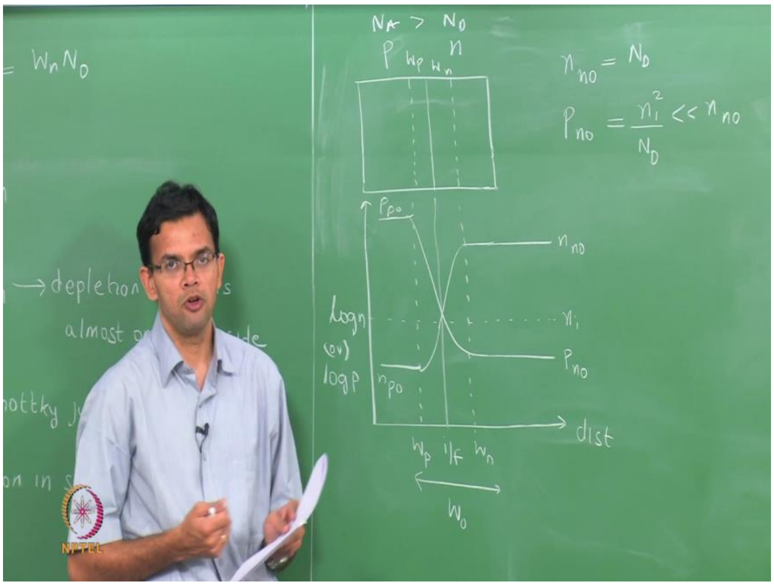

Let me, just re draw p-n junction here this is the interface so, the p side and n side. We have NA and ND as the concentration of acceptors and the concentration of donors and we have NA greater than ND. We just saw this means, the depletion with larger than the n side the depletion region on the p side and there is a larger depletion with on the n side. Because, is Wp and than Wn so we plot a log of how the concentration of electrons or holes change as a function of distance.

So, I will plot a log of n or log of p as a function of distance. So, let me again mark my interface this is Wp, this is Wn so, this represents the depletion region. Let me, also mark ni; ni is the intrinsic career concentration in the case of electrons and we are in the n side the concentration of electron in the n side let me called n no is nothing, but ND. The concentrations of holes in the n side we can use the law of mask of action nothing, but ni square over ND.

So, usually this is much less than n no similarly, the concentration of holes the p side is just NA and the concentration of electrons in the p side is just ni square over NA. These are all just notations, but we have taken this calculation before when we look intrinsic semi conductor. If we go had and plot this, this is n no if it is equal to ND at the depletion region the concentration begins to draft.

Because, we said we have a depletion region because electron move from end to the beside the concentration drafts. And finally, in the beside the concentration because equal to n po we can do the same for the holes and we said, the hole concentration is higher the electron concentration. We said NA more than ND let me just draw this axis bit up so, that this is ppo.

Once again, when we reach the depletion region this number is going to drop because, you have holes moving from the p side to the n side. And then, far away from the junction we have the concentration p no. So, this graph shows you how the electron and the whole concentration change as we move from the n to p or from p to n. So, this difference is related to the built in potential.

Because, what the potential does is the reprudance further motion of electrons from n to p or holes from p to n. So, in this way it is similar to what happens when we have a Schottky junction. So, there also we had a built in potential that prevents further motion of electrons.

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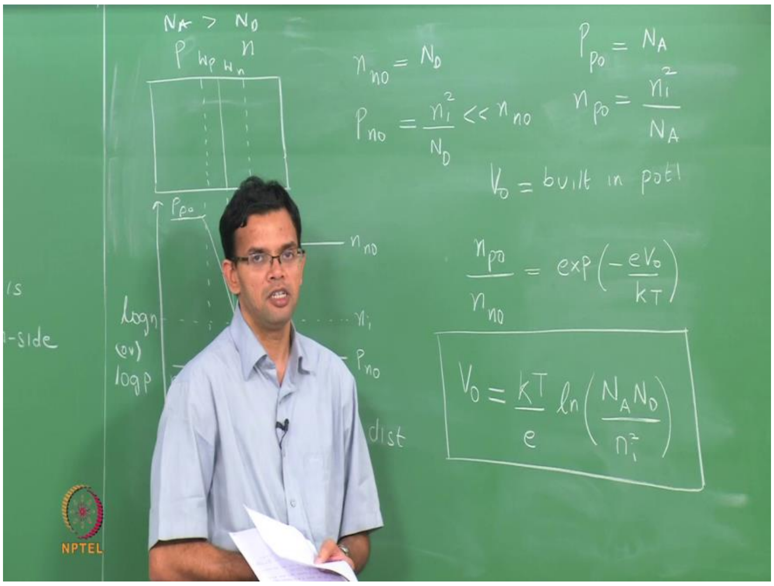

So, V0 is the built in potential it is related to the concentration of electrons on the n and the p side. So, n p0 which is the concentration of electrons in the p side by n n0, which is the concentration of electrons on the n side is equal to exponential minus ev0 over kT. So, once again V0 represents the barriers that the electrons have to overcome in order to go from the n to the p side.

We can substitute these values n0 n p0 and n n0 and re arrange this expression to give you your contact potential. V0 is nothing, but kT over e ln of NA ND over ni square. We get this expression, by taking natural ln on both the sides and for substituting for these values and re arrange. So, the contact potential in the case of a p-n junction depends upon the concentration of the acceptors and the concentration of the donors and also the intrinsic carrier concentration.

We can also calculate the width of the depletion region that forms when we have a p-n junction. Let me, just re draw the junction again.

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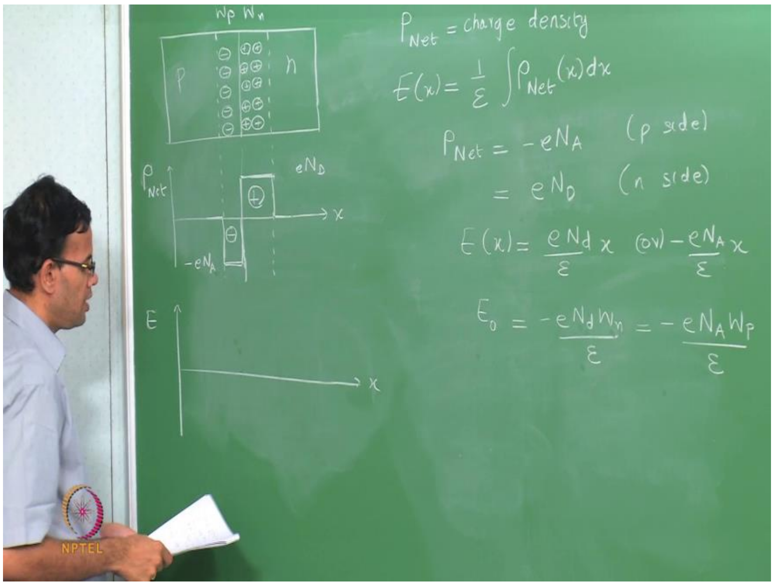

So, we have a p-n junction with NA greater than ND so that, we have some Wp which is smaller than Wn. So, we said that in the depletion region the access electrons and the holes recombine and get annhilated. So, that you have a net negative charge on the p side and net positive charge on the n side. I am putting two positive charges to indicate that we have a wider depletion region on the n side.

If you plot the charge density as a function of distance so, rho represents the charge density as a function of distance. We can usually say that the depletion region is dividing of carriers so that; the charge density is just a delta function. So, let me plot the interface this is the n side so on the n side, the charge density is just given by the concentration of the donor ions.

So, this is plus ND because we have positive charge on the p side the charge density is given by the acceptor ions which have a negative charge. So, that this is minus eNA and the total charge has to be 0 which means, the positive charge in the n side has to balance the negative charge on the p side. So, the areas under these two graphs are the same. We can relate the charge density to the electric field the equation is the electric field.

E as a function of x is just 1 over epsilon, where epsilon the permittivity of the material integral rho Net as a function of x dx. So, we just said that the charge density is a delta function and it is a constant. So, we saw that rho Net is equal to minus eNA this is the p side and it is equal to eND it is the n side. We can substitute for this here and then integrate over the entire width of the depletion region to get the electric field e.

So, the expression for the electric field e is equal to eND over epsilon x or minus eNA epsilon x. We can define an E0 which is equal to minus eND Wn epsilon which is equal to minus eNA Wp and these two are the same. Because, we know that to maintain charge neutrality Nd times Wn is equal to NA times Wp. So, we can plot the electric field e as a of function distance so, I will use the same plot here electric field e the function of distance, the electric field is essentially negative.

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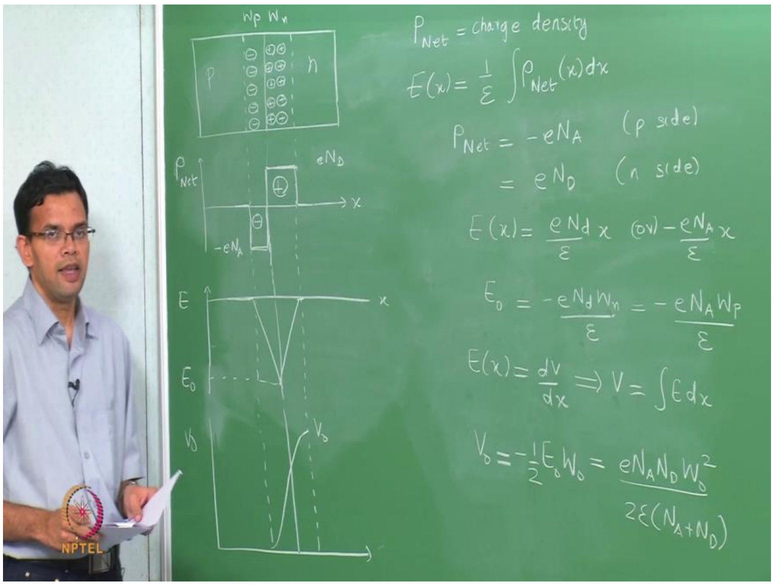

So, let me just re draw it only on the negative side that is my interface this is the p side this is the n side outside. The depletion region, the electric field is 0, but within the depletion region E is a linear function of distance and the maximum value is E0. So, the maximum value of E is E0; E is also related to the potential by the expression E dv over dx.

Which means, the potential V in integral of E dx we can substitute this expression and do the integration the total potential, which is the contact potential; which we are interested in goes from the p side to the n side and V0 is nothing, but minus 1 half E0 and W0, where W0 is the entire width of the depletion region. That is equal to eNA ND W0 square over 2 epsilon NA plus ND we can plot V0 as a function of x, if you look at this expression V is the integral of E dx; E is the linear function in x.

So, the integral of a linear function is a parabolic function. So, if you plot V0 over x that is my interface that is the n side. That is the p side potential goes from 0 up to the contact potential V0. And the expression for V0 is given here; let me re arrange this to get the total width of depletion region in terms of the contact potential.

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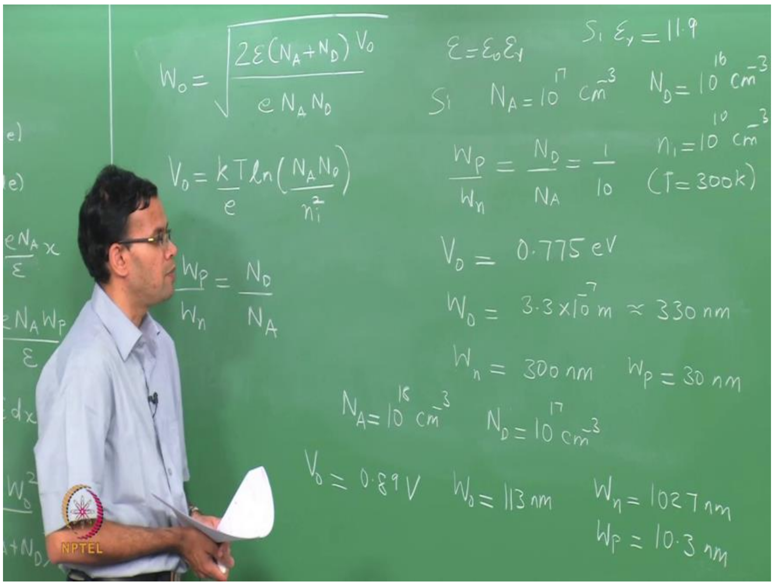

If you re write this expression we get W0 is nothing, but square root of 2 epsilon NA plus ND times V0 over e NA ND epsilon, which is the permittivity of the material is nothing, but epsilon not r nothing, but epsilon not, which is the permittivity of free space times epsilon r which is the relative permittivity of the material.

In the case of silicon epsilon r we saw this earlier has value of 11.9. So, we have an expression for the contact potential kT over e ln of NA ND over NA square you are have an expression for the total width of the depletion region. And we also saw, that the individual widths are inversely proportional to the concentrations. So, let us plug in some numbers to get a sense of what these values are.

So, will take the example of silicon with acceptor concentration NA equal to 10 to the 17 per Centimeter cube; in donor concentration 10 to the 16 per Centimeter cube. So, Wp over Wn is nothing, but ND over NA which is 1 over 10. So, the width of the depletion region in p side is 10 time smaller than that of the n side and that is because, the concentration of acceptors is 10 times more than the concentration of donors.

In the case of silicon we know that, the intrinsic carrier concentration is tend to the 10 and you are doing these calculations at room temperature so, T is 300 Kelvin. So, we can calculate the potential we will just use this expression where we plug in the values. If we do that V0 0.78 electron volts, you can also calculate the width of the depletion region W0 once again it is a straight case of using this equation and plugging in the numbers.

If you do that we get a value of W0 to be around 3.3 times 10 to the minus 7 meters or proximately 330 nano meters. So, the total width of the depletion region is slightly a less than 1 micron it is around 0.3 micro meters. You can also calculate the individual width by using the ratio if you do that we get Wn is to be around 300 nano meters and Wp to be 30.

So, that this ration of 1 over 10 is maintained; the width of the depletion region is inversely a proportional to the concentration of the carriers. So, if you have a higher value of NA or ND then the total width will be lower. If you want to re work this with NA increased 10 time put 10 to the 18 per Centimeter cube similarly, ND is 10 to the 17. So, you increased both NA and ND 10 times, but the ration is still the same.

We can re do this calculations let me just write it down V0 is also higher because, V0 is equal to NA times ND. The potential V0 is around 0.89 volts the total width is lower W0 it is around 113 nano meters. And once again, the width on the n side is 102.7 and the width on the p side is 10.3. So, we can reduce the width of the depletion region by increasing the carrier concentration on the p and the n side.

So, this is the p-n junction as far as silicon is concerned. Now let us, just look at what happens if we change the material. What we want to know is how the contact potential changes when we change the material.

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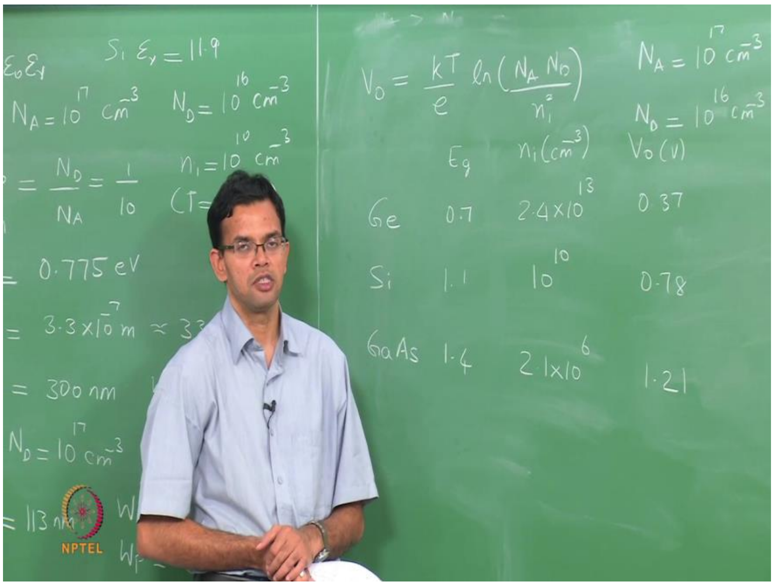

Now, V0 is related to kT over e ln of NA ND over ni square for sake of comparison I am going to keep NA equal to 10 to the 17 and ND equal to 10 to the 16. But V0 also depends on ni which is the intrinsic carrier concentration and that depends upon the band gap. So, higher the value of ni which happens if you have a lower band gap when smaller is the contact potential.

So, if you look at 3 materials: Germanium, Silicon, gallium arsenide. So, we are forming p-n junctions between 2 Germanium p and n same with silicon same with gallium arsenide. The band gap values at room temperature 0.7, 1.1, 1.4 ni is different we have done these calculations before for these intrinsic materials 2.4 times 10 to the 13, 1 times 10 to the 10, 2.1 times 10 to the 6.

So, these are the values of ni and if you plug in this equation V0 in volts is 0.37, 0.78 and 1.21. So, the contact potential increases as the value of ni goes down and this happens when you have a larger band gap. So, toady we have looked at a p-n junction that is in equilibrium that is there are no external potentials applied.

We saw that, we have electrons moving from the n side to the p side holes moving the other way and this creates a depletion region. In the next class, we are going to look at the IV characteristics of a p-n junction and what happens when we applies a bias to this junction.