Fundamentals of Semiconductor Devices
Prof. Digbijoy N. Nath
Centre for Nano Science and Engineering
Indian Institute of Science Bangalore

Lecture – 23
Introduction to Schottky Junction

Welcome, so will continue with Schottky junctions, if you recall in the last class we had introduced why metal contacts are very important. What are the 2 types of contact you can form in semiconductor and depending on the application you need both type of contacts and metal contact is very very crucial to measuring devices, any device, to wire bonding devices and packaging and so on ok. So, metal contacts are very critical and we that we are trying to understand a metal semiconductor contact. So, towards the end of the class we had introduced this, the band diagram some metal semiconductor and we tried to equalize the Fermi level.

We showed that in an equilibrium you form a Schottky barrier and there is a depletion width and then there is a built in potential, I told you that because of the barrier its difficult for electrons to move across that is why you get a non-linear sort of a Schottky contact that we call. In the reverse biased you know the metals the electrons from metals to semiconductor they have find it very difficult. The forward biased the electrons from semiconductor metal they progressively increase you know as they move across, because you reduce the barrier just like in a p-n junction it is just like in a p-n junction.

So, today we shall do a bit of a derivation of the depletion width, the built in potential, maybe the current equation and also how do we make an ohmic contact and so on. There is a lot of things actually in metal semiconductor junction. So, let us come through the whiteboard and from the last you know last slide that we had shown here.

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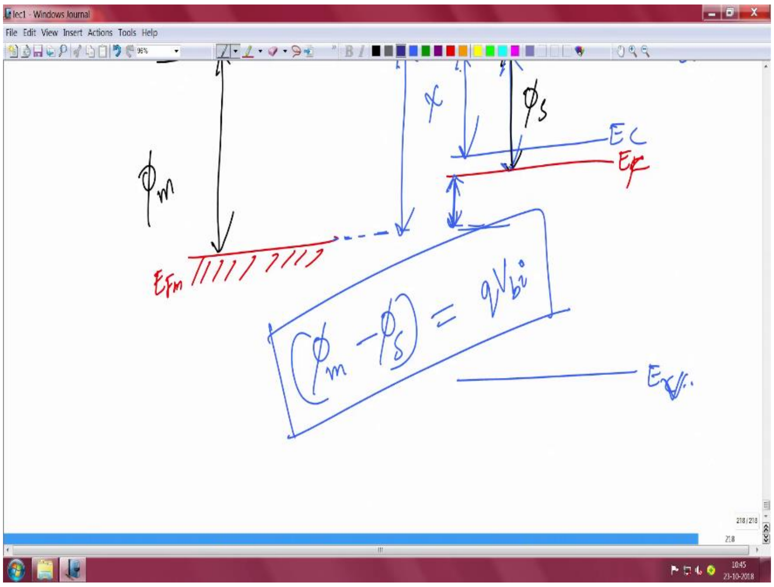

So, if you recall from the last lecture if you have a semiconductor metal junction in equilibrium.

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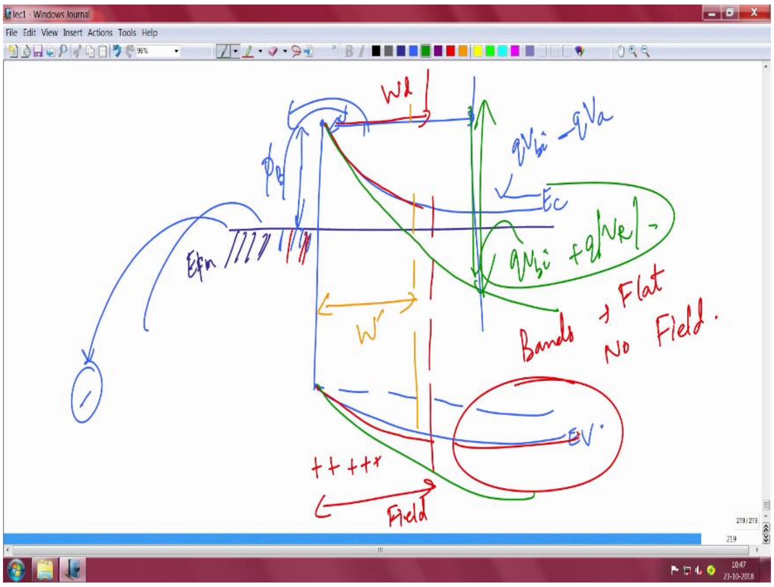

This is your everywhere the Fermi level is the same in equilibrium, but there is a barrier here and then there is a depletion. So, what happens is that I told you this is a barrier Schottky barrier height from the metal Fermi level to the tip of the conduction band here this is conduction band right, this is valence band and then there is a depletion that has formed which is this W_d and in the depletion there are no carriers only positively charged ions are there.

Because the mobile electrons are basically comes to the metal to equalize the Fermi level if you remember from the last class, there is also a field in this region this region also has a field because there is a bent in the conduction band and from the valence band right and then beyond this part there are no fields here this is neutral region ok. The bands are flat the bands are flat and then there is no field here there is no field here.

So, this is what we have learned here and then of course, another thing we told is that this is the building potential that is formed, the built in potential can be given by the metals and the semiconductor work function difference right and if you apply a forward bias which means. Of course, when you apply forward bias or reverse bias, there will be some current maybe large current maybe small current that is a different thing. But the moment you apply forward biased which means you are applying a positive biased to the metal then what will happen is that it will attract electrons from the semiconductor.

It will attract electrons from the semiconductor, two things that will happen is that one, your depletion will become narrow your depletion which will become narrower and then secondly your bands will rise up like this ok. So, your effective voltage that you are dropping here will reduce by $qV_{bi} - qV_a$, where V_a is the applied voltage. So, the depletion reduces, the barrier reduces so more currents will flow.

We will come to a mathematical derivation in a bit. So you essentially have a lowering of barrier in forward biased and in reverse biased when you apply negative voltage into the metal what will happen is that a reverse will takes place, which means your depletion will now increase because you are trying to push electron from here to there which is very difficult anyways so very little current will be there.

So, depletion will increase and what will happen is that your depletion width also will increase and depletion the barrier also will increase. So, this barrier also will become $qV_{bi} + q|V_R|$, the reverse biased that you are applying. So, this will also reduce increase and then that is reverse biased condition.

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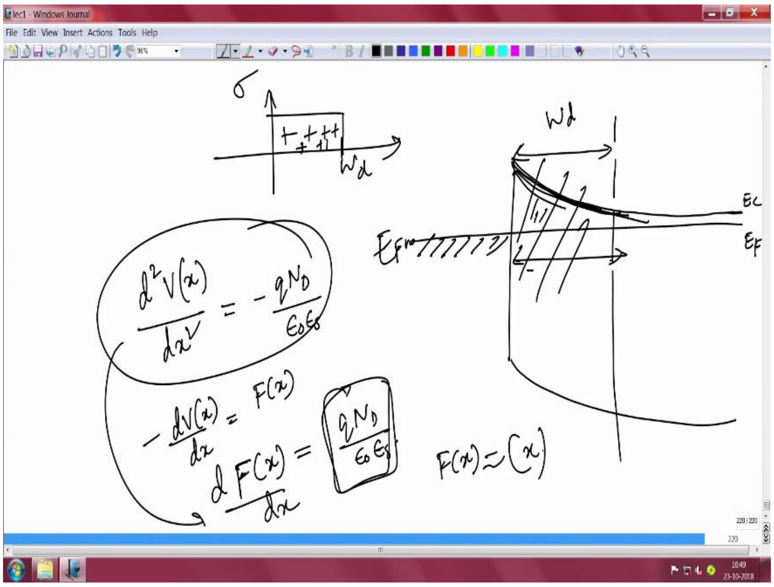

So, now let us take the equilibrium condition only will do an equilibrium analysis here. So, let us take an equilibrium condition here this is your metal Fermi level those are in biased conditions and when current will flow am talking about equilibrium condition here. So, this is your equilibrium of course am not drawing it very well, but your Fermi level will be constant here and then your conduction band valence band will look like that.

This is an n type doped semiconductor, this conduction band and this Fermi level the difference will be constant in the neutral region. This is your non neutral region in the sense that this is a depletion region there is a field here. So, I told you in this depletion region you have positively charged, if you plot the charge here then this is up to W_d you have positively charged ions ok. If you have positively charged ions; you see the potential is changing here, the field also will changed there.

So, you do the same thing that we have done in pn junction which is to solve the Schrodinger equation or the Poison equation sorry, $\frac{d^2V(x)}{dx^2}$, V is the potential along, this is electron energy. So, the potential will be the mirror image of this, if you remember and this will be equal to the negative of the charge that is stored here, in this region from 0 to $W_d$the charge that is stored is qN_D that is the positive charge stored. So, there is a negative here that is the law and ϵ_0, ϵ_s is the semiconductor dielectric constant.

So, if you recall then what do you have to do is that $\frac{dV(x)}{dx} = F(x)$. So, I can say $F(x)$ the field actually the field will also keep changing here is equal to $\frac{qN_D}{\epsilon_0\epsilon_s}$ right the field will be there. So, you have to integrate out if you want to this is $\frac{dV(x)}{dx}$ this is field right this is the field that is changing, if this is the field that is changing then the field will actually keep changing here right.

If you put this equation then it will look like $\frac{dF(x)}{dx}$ is equal to this right. So, the $F(x)$will basically vary linearly the derivative of field is basically this. So, the field will vary linearly in terms of x. If you did not do an integration and then you do the boundary condition analysis what will you get.

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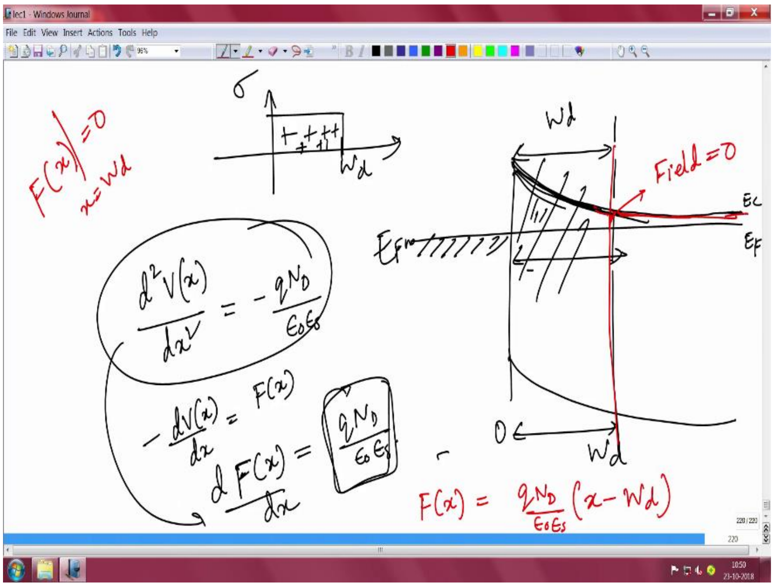

You basically have to integrate from 0 which is this position to W_d which is this position ok, over the depletion length only you have to basically do the integration and keep in mind the boundary condition is that at the end of this depletion at x equal to Wd at the this point your field will go to 0 field will become 0, because after that point of field is 0, the bands are flat at this point of field will go 0 till this point of field will be there.

So, the field will be 0, $F(x)$ will be 0, for $x = W_d$ at the edge it will go to 0 ok. With that boundary condition, you can find out the field and the field you know expression for field will look like $F(x) = \frac{qN_D}{\epsilon_0\epsilon_s}(x - W_d)$ that is what it will look let me come to a new page.

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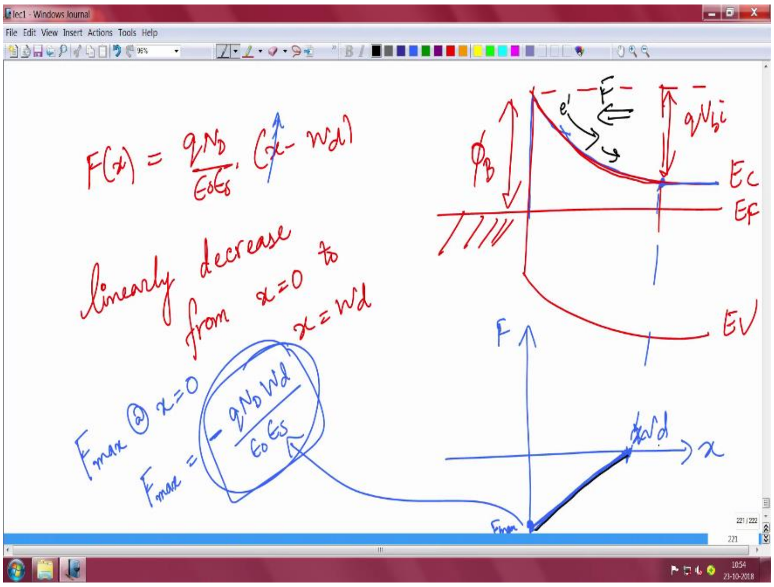

So, this is your metal Fermi level, this is your Schottky junctions that has formed, this is equilibrium E_c, E_F, E_V, this is your $\emptyset_B$ the Schottky junction which is formed, this is your qV_{bi} the built in potential that has formed, am talking about the depletion region here which is this Wd.

So, in the depletion region when you do that I just told you right. So, the field $F(x)$ will look like q, once you do the once you solve this integration. Once you solve this integration with the boundary condition that with the boundary condition that your field will become 0 at this point field will become 0, at that point you basically get $F(x)$ ok. You get the solution as $F(x) = \frac{qN_D}{\epsilon_0 \epsilon_s} (x - W_d)$.

So, the field actually linearly decreases, the field will actually linearly decrease, there is a minus sign here actually I guess no thats fine the field will actually linearly decrease from $x = 0$ to $x = W_d$. Of course, it will nearly decrease that because the charge is constant, if the charge is content the field will linearly vary, if the field linearly varies the integration of linear function is quadratics so they potential will vary quadratically. So, of course, this is a parabolic function here just like an p-n junction.

.So, what it means is that the field will become, the field will decrease from x equal to 0 from this point this is x equals 0 point, the field will keep reducing and the linearly and the field will eventually becomes 0 at this point at this point x because after that point a field is 0 the bands are flat.

So, if I plot the electric field this is only the band diagram right, if I plot the electric field with respect to x how will it look like ok. So, if I plot the electric field with respect to x how it look like ok. So, this is electric field this is x so the field will become 0 at this point, at $x = W_d$, the field will become 0 the field will be maximum field will be maximum at $x = 0$ the magnet am talking about the magnitude.

The field will become 0 when the field will become maximum when x is equal to 0 and that field value will be given by $-\frac{qN_D W_d}{\epsilon_0 \epsilon_s}$ that is negative here. So, this point this point for example is this value which is F_{max} and the field will reduce linearly from here to there just like in a p-n junction except that there is no p side here. The field will actually reduce from this point to this point linearly. So, the field will reduce linearly this is the maximum field that you can handle and it is negative in direction because, you can see that if you put an electron here think of it as a rolling slope the electron will roll down this side.

So, the field is in this direction which means negative that is why the field is negative here. So, the field will change linearly and decrease eventually it will become 0 and what is the potential that will change now, the potential will basically you have to do a integration of the field.

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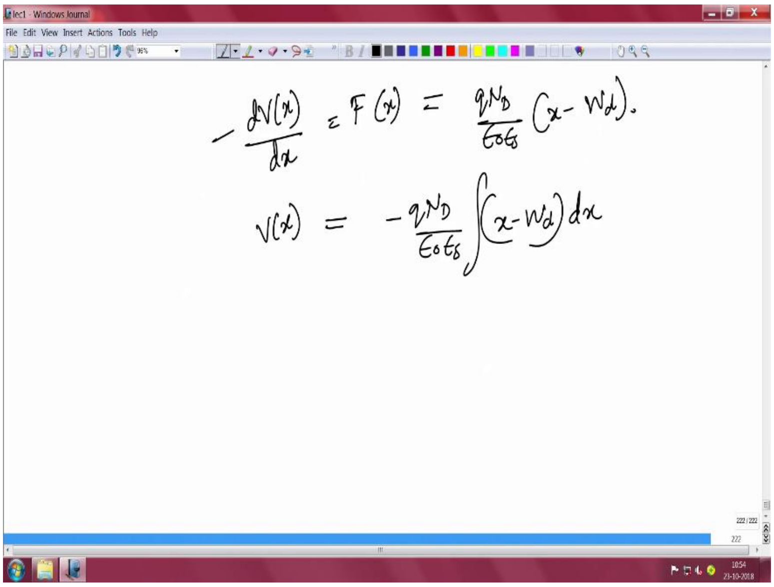

So, I told you $-\frac{dV(x)}{dx} = F(x)$ and that is given by $\frac{qN_D}{\epsilon_0 \epsilon_s}(x - W_d)$. So, if you integrate it out you will see that this is $V(x) = -\frac{qN_D}{\epsilon_0 \epsilon_s}(x - W_d),$ you do a dx ok. You want to find out actually the potential drop, I mean you see the if this potential you keep changing as a function of x at any point x the potential will keep changing.

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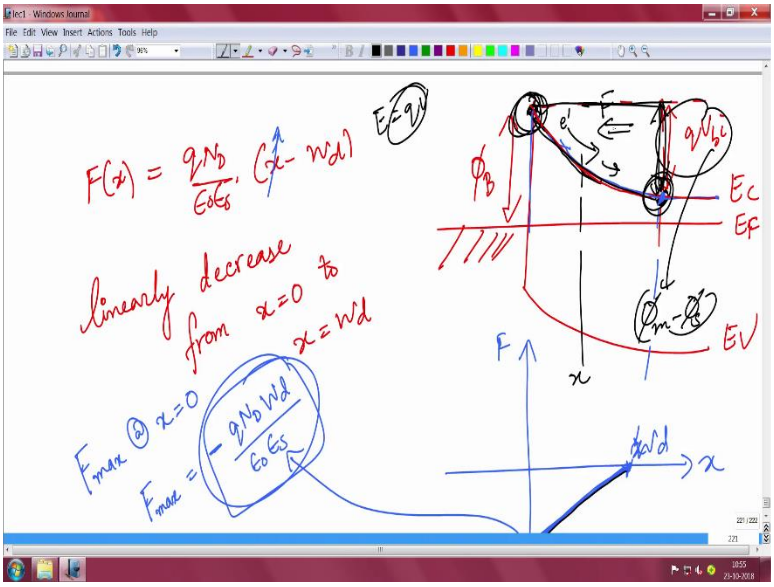

But I want to find out this potential drop total drop, which means I want to find out the potential at this point minus the potential at this point, that drop is actually that the built in potential and the built in potential is given by $\emptyset - \emptyset_s$ that you also know. But I want to find out in terms of depletion and doping and other things right. So, you see I want to find out what is the drop the total drop here.

So, I need to find out the potential here the potential here and minus subtract that, this is a high energy. So, this will be the lower potential these are the lower energy this means it is the higher potential because potential and energy they have a negative sign q the charger will have electron right, $E = qv$, this q is equal to negative that is right ok.

So, at any point x you can find that a potential, but our objective is the difference of these two potential at this side. So, if you do this it will eventually come out to be the same as p-n junction thing only.

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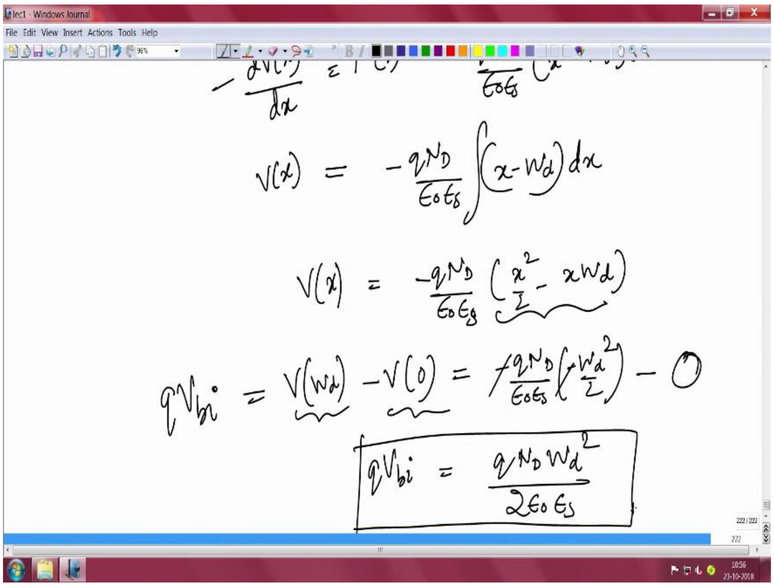

So, $V(x)$ will eventually be $-\frac{qN_D}{\epsilon_0\epsilon_s}$, this will be $\frac{x^2}{2} - xW_d$. So, you now put $V(W_d) - V(0)$ what will this be that is the difference the potential difference that you will get ok, $V(W_d) - V(0)$ means the potential at this point minus the potential at that point. So, that you will do it will come out we have to put first W_d here which means it will be $\frac{qN_D}{\epsilon_0\epsilon_s}$.

If you put W_d here, it will be $\frac{W_d^2}{2} - W_d^2$, $W_d \times W_d$which will be $(-\frac{W_d^2}{2})$ minus this will be everywhere 0 0 it will be 0 0. So, what will come out to be is that the built in potential will be equal to q this negative will go and $\frac{qN_DW_d^2}{2\epsilon_0\epsilon_s}$ like the same expression for junction built in potential and p-n junction if you remember ok.

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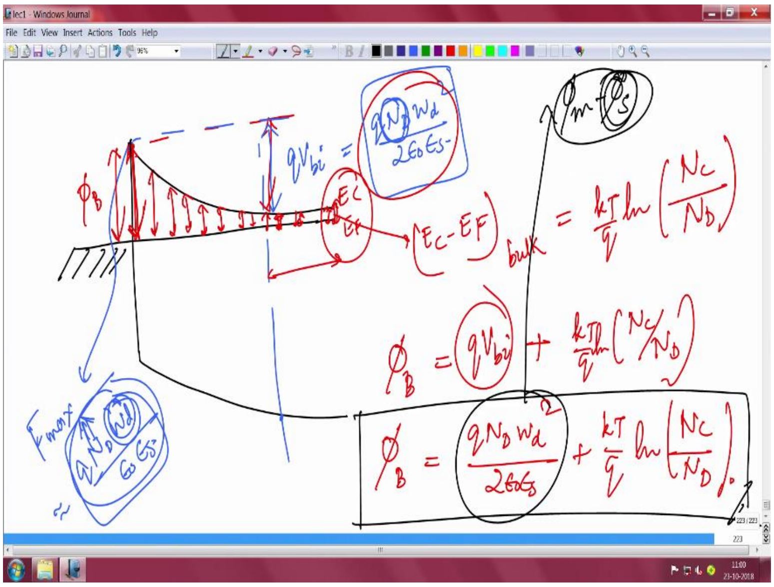

So, essentially in a semiconductor metal junction also just like in a p-n junction it is basically like a 1 sided p-n junction at 1 side being metal, there is no p type here that is all basically in p type there is another potential drop that happens now.

So, essentially this built in potential that you have just from the derivation that we had done can be written is $\frac{qN_D W_d^2}{2\epsilon_0 \epsilon_s}$ and the field keeps changing from this point to this depletion point here. The field is maximum here at this point and that field is given by $\frac{qN_D W_d}{\epsilon_0 \epsilon_s}$ ok.

So, you see these are very important parameters that we have talked about here if your doping increases what will happen, if your doping increases your depletion actually will reduce you know if your doping increases a depletion will reduce. But your so this will if you do doping increases this will reduce, but this will increase eventually the field will increase at this point if your doping increases ok. If your doping increases your field will eventually increase ok.

Now, these are the 2 things that we should keep in mind very very well very very well and you remember I will come to this gap this gap is actually $E_C - E_F$, here see the $E_C - E_F$, gap is different here and the $E_C - E_F$ gap is different here this is huge this is $\emptyset_B$. The $E_C - E_F$ gap actually is $\emptyset_B$ here and the $E_C - E_F$ gap keeps decreasing, decreasing, decreasing, decreasing, decreasing eventually it becomes here constant and then becomes constant here, because there is no change here no field here. So, I will call this $(E_C - E_F)_{bulk}$, bulk as in like deep inside the semiconductor and that $E_C - E_F$ is actually given by $\frac{kT}{q}$ from Boltzmann equation $\ln(\frac{N_C}{N_D})$ and assuming 100 percent ionization.

So, N_D is equal to the free electronic concentration, N_0 which is the equilibrium concentration, the same as N_D. So, $N_C - \frac{N_C}{N_D}$ this is your conduction band you know the Fermi level difference here. So, you know see this Schottky barrier height $\emptyset_B$ is actually this built in potential qV_{bi} plus this gap here which is $\frac{kT}{q}$ $\ln(\frac{N_C}{N_D})$ ok. So, your built in potential actually is and this is this $\frac{qN_D W_d^2}{2\epsilon_0\epsilon_s} + \frac{kT}{q}$ $\ln(\frac{N_C}{N_D})$, this is your Schottky barrier height.

$$\emptyset_B = \frac{qN_D W_d^2}{2\ \epsilon_0\epsilon_s} + \frac{kT}{q}\ \ln(\frac{N_C}{N_D})$$

The Schottky barrier height is this ok, so you keep that in mind there with your doping this will not change so much because this is still given by $\emptyset_m - \emptyset_s$ in the sense that this metal semiconductor of functional keep reducing with higher n type doping. So, this difference will slightly start to become smaller so the built in potential is slightly become to start smaller when a doping increases ok.

So, this is a you know you got the expression for built in voltage now you have got the expression for field, you have got the expression for the total Schottky barrier height, so these are good things that you have learned. Now you might also want to do some you know numerical, for example to actually gain understanding of how these things are working if you might be given the doping. For example, you might be said that I have a semiconductor here.

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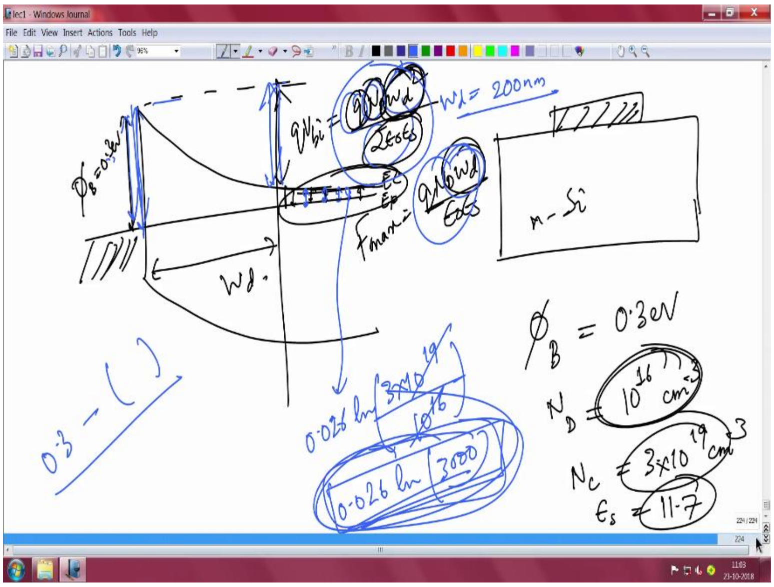

I have a semiconductor say n type semiconductor I put the metal here, the metal from say Schottky barrier height of say you know 0.3 ev, this is the Schottky barrier height that has formed. So, you can immediately think that this barrier height is 0.3 ev.

This is like this and now suppose you are given that doping as N_D equal to for example, $10^{16} cm^{-3}$ and your conduction band density of states N_C is always given say this is $3 \times 10^{19} cm^{-3}$, am just telling you an example ϵ_s for silicon is you know 11.7.

Then can you find out the built in potential here, yes I can find out the built in potential first I have to find out the depletion, how will you find out the depletion actually that is very important. To find out the built in potential here work functions are not given you need to find out $\frac{qN_D W_d^2}{\epsilon_0 \epsilon_s}$.

So, $\epsilon_0 \epsilon_s$ will have here, ϵ_0 is vacuum that mean dielectric constant, N_D is given here, you only need q you know, only you need W_d, you do not know W_d, you also want to find out the maximum field, for that also you need $\frac{N_D W_d}{\epsilon_0 \epsilon_s}$. You see W_d is there how will you find out W_d now that is a very relevant question ok, this is your W_d how will you find out W_d.

So, you see your conduction band here this is $E_C - E_F$ and that difference we know that difference we know right. How will you know this difference $E_C - E_F$ this difference because, this doping is given N_D this N_C is given this particular difference this particular difference that you find out will be given by $\frac{kT}{q}$ which is $0.026\ ln\frac{N_C}{N_D}$ right. So, this will be $\frac{3\times10^{19}}{10^{16}}$, so this will be $0.026\ln(3000)$ ok.

So, you find those value once you find out that value you know this gap know you know this gap, now you also know this you also know the Schottky barrier height is 0.3. So, you subtract this quantity from this, so if you subtract 0.3 ev which is this minus this quantity whatever that quantity is I do not know it may be 0.1 whatever right you can calculate that value. So, what you will get after I subtract that out is that you will get this value, once you know that value you can you know this everything you know you do not know the W_d you say find out W_d .

So, you will find out the depletion width suppose it comes out to be 200 nanometer, am just giving an example then you just use that here to find out the field and this value of the built in potential is of course obtained by this minus this. So, there is the that way you can solve the numerical problems excuse me that way you can solve the numerical problems for your metal semiconductor junction. Now this is a metal semiconductor junction right there is another kind of metals and what if you have to ask another question.

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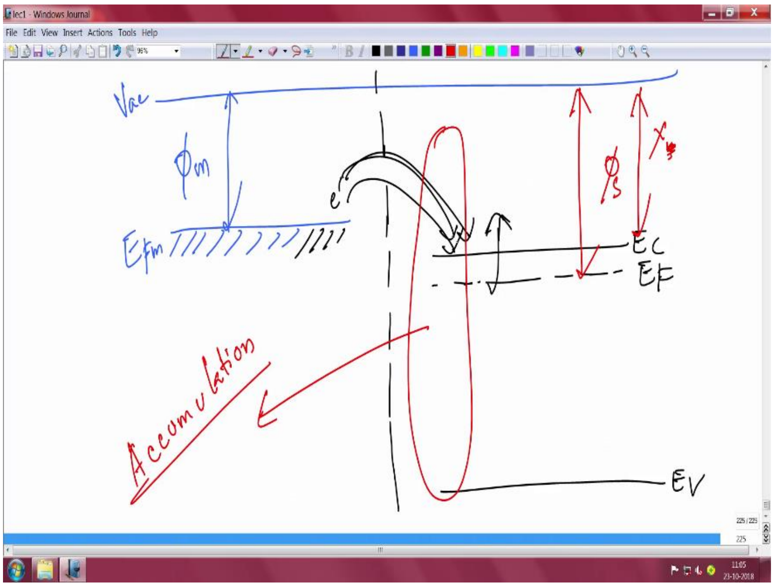

Suppose I have a metal here Fermi level so this is your vacuum level. So, this is your $\emptyset_m$ for example, what if I have a semiconductor such that the conduction band is here, the valence band is here and the Fermi level is here, n type doped it is also n type doped. Now the Fermi level is below the metal, you see the Fermi level is below the metal. So, the metal will give electrons from here to there the metals will keep giving electron, the metal will keep giving electrons until the Fermi level comes up and balances with the it becomes equal with the metal ok.

So, what will happen is that at the junction and this is a different kind of junction by the way because, the work function of the semiconductor this is actually larger than that of the metal this is your electron affinity. So, what will happen is that electrons will be given donated by the metal to the semiconductor and because it is giving electron this part will have an excess electron because, they are coming you know and that is why that part will have something called Accumulation. Accumulation as in electrons from metal have come and accumulated here and the Fermi level will rise up and how will it look you know eventually it will eventually look like this.

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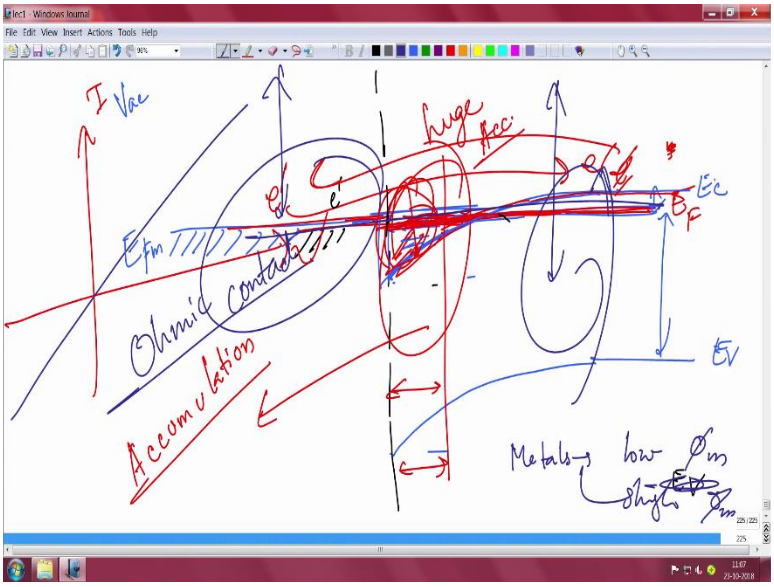

So, it will the Fermi level will basically be balanced the Fermi level will eventually be balanced and far away from the junction far away from this is Fermi level far away from the junction the conduction band, the valence band they will be same with respect to the Fermi level. So, these difference will remain the same this difference will remain the same far from the junction.

But I told you we fix this point and it was initially if conduction band was here if you remember and a valence band was here right. So, what will happen is that it would go like that it will go like that to conduction. See the Fermi level is actually now on this Fermi level this is the Fermi level is actually going on top of the conduction band, because the conduction band is this blue one and the Fermi level is this red one for example, this is going. So, the red Fermi level is able to conduction band at this point.

So, this point will have a huge excess carrier of electron because, the conduction band is above the Fermi level or sorry a Fermi level is above the conduction band which means you see you see think it very carefully the Fermi level which is ideally below the conduction band has become above the conduction band, now is the conduction band has come down here. There is a huge accumulation of actually electrons here like an electron gas and this thickness is very narrow because a lot of that lot of very huge carrier of electrons can be generated by a small change in the conduction band ok. So, this is accumulation region you do not find out any accumulation depth here, because it is only a couple of nanometers or something it is very thin and you see electron from here can easily go here an electron from here can easily come here no barrier.

So, for this kind of contact if you plot I versus V you will get a linear contact like that. So, this kind of a junction is called Ohmic junction or Ohmic contact. So, what we learned here is that to form an ohmic contact your metal work function should be smaller than the semiconductor work function, only then the semiconductor will come up like this and will form an Ohmic contact. So, ohmic contacts are formed when metals have low work function low work function and if metals have high work function then you form a Schottky sort of a junction ok. So, this is about n type right, similarly for p type it will be opposite actually.

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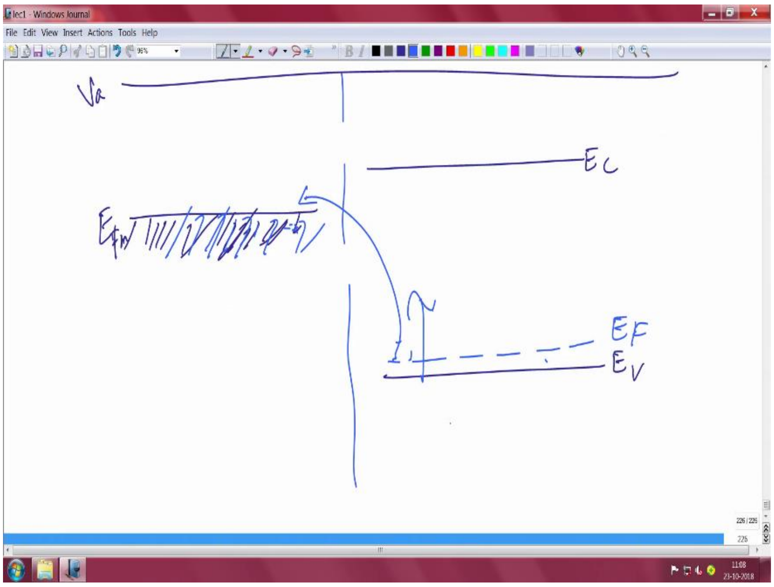

So, for example, if you have a Fermi level here this is the vacuum level for example and suppose I have a p type semiconductor suppose this is my conduction band let me draw it a different way suppose I have this is Fermi level here. So, suppose this is conduction band, this is valence band and suppose I have a Fermi level a p typed dope, you know Fermi level is here what will happen then. In n type semiconductor if a Fermi level is below conduct, the metal Fermi level you will find ohmic contacts just now we saw. In p type it is opposite if the Fermi level is below the Fermi level of the semiconductor is actually lowered in the Fermi level of the metal then you will form a Schottky contact.

Why because a Schottky contacts in this p type will be formed in by not on the conduction band side. So, in this case what will happen is that you know this the Fermi level here will have to balance out here right, the Fermi level will have to balance out here which means essentially this will give out holes to this, you can think of like that it will give our holes to this if this fermi level will come down and far away from the junction the Fermi level conduction and valence band everything has to remain similar. So, what will happen eventually is that it will look like this.

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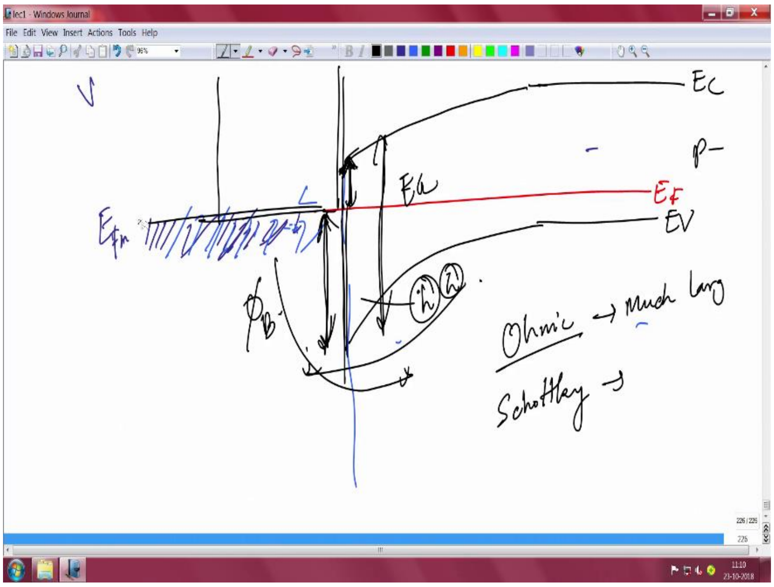

The Fermi level is constant everywhere and your valence band will have to be maintaining the same distance with Fermi level ok, forget the vacuum level now, vacuum level will band accordingly and this is your suppose conduction band this is a Fermi level this is p type semiconductor and it will band like this it will band like this.

So, this barrier that has formed is the Schottky barrier $\emptyset_B$ this is your Schottky barrier with the because, this is now hole conduction this is hole, holes will try to come, holes will try to go right. So, this barrier is the Schottky barrier and this barrier is the Schottky barrier for holes and unlike in n type semiconductor, this is not that straightforward to calculate, it is still given by the metal semiconductor work function difference sort of thing. But there is a more there is more to it actually you know because, this gap is given by this band gap this is the band gap of the semiconductor as you know minus this ok.

So, is the given by the band gap of this minus this and what is this is basically the band that has happened ok. So, p type semiconductor [FL] for p type semiconductor to form ohmic contact it will be opposite. So, this has formed the Schottky contact right, a p type semiconductor you form the Schottky contact by having you know metal whose work function has lowered and that of the you know the semiconductor of function. To form an ohmic contact the metal needs to come the metal needs to have a much larger work function much larger work function, only then only if you have a very large work function of the metal. If the metal work function is like this is E_{Fm}.

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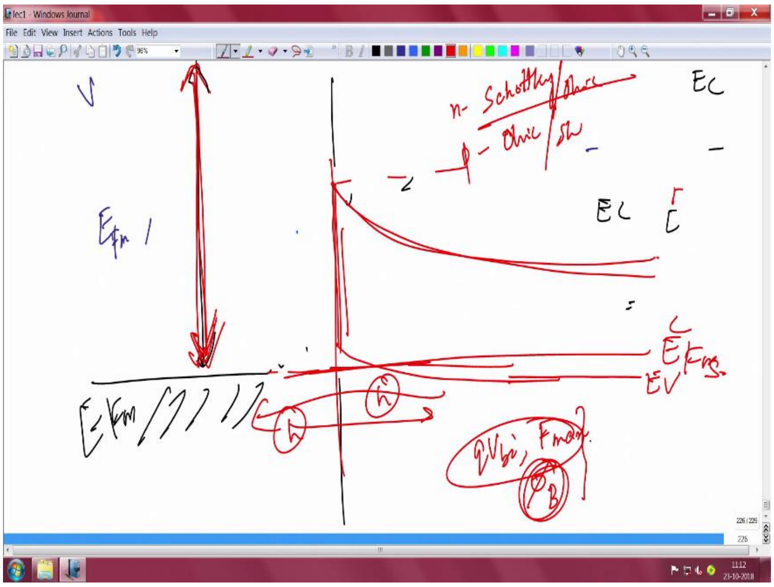

Only then you will be able to form an ohmic contact, how because if you have metal work function which is like this then, suppose am drawing the metal work function like that not drawing here, am just drawing a metal work function from here and the conduction band is here, the valence band is here and the Fermi level is here, only then it will only then when you form a junction how it will look like is that this will come here and then your conduction band, valence band will look like this is your valence band, this is your conduction this is your conduction band this is your valence band sorry actually it has to match up accordingly.

So, your conduction your Fermi level is this one, Fermi level of the semiconductor, this is your valence band and the valence band will band like this, the conduction band will band like this same band gap of course. So, you see the holes here will have no barrier to move here, holes will have no barrier to move this will give you an ohmic contact. To make an ohmic contact you need a large work function of the metal, because metal should work function very large work function are difficult to find. So, making a p type contact becomes generally more difficult if the band gap also becomes large.

So, the wide band gap of metals metal semiconductors very difficulty in forming, a in forming actually good ohmic contact. So, remember on the n type we can form Schottky and ohmic similarly we can form on p type also we can from ohmic and Schottky type contact two types of contacts are there.

We discuss the depletion and built in potential case by taking the example of the n type semiconductor, but similar things can be done for p type semiconductor numerical can come for that ok. So, we know the built in potential expression, we know the electric field expression, we know the semiconductor the Schottky barrier height equation. Now I told you that the current flow will be obstructed because of this Schottky barrier height, if you have an ohmic contact then carrier flow will not be obstructed, so it is a linear contact.

So, in the next class what we will do is that we will try to you know we will end up the class here, in the next class what we will do is that we will start with the equation for current voltage characteristics for a Schottky type contact. So, for ohmic type contact is just linear I-V it is like V equal to IR right. But when you have a Schottky barrier will take the example of n type semiconductor, when you have a Schottky barrier then I qualitatively told you that in forward biased and in reverse biased how the I-V will look like, the reverse characteristics, the forward turn on, I qualitatively told you. But we shall derive that quantitatively we shall derive that quantitatively and you will see why and how that Schottky type behavior comes from in a mathematical way mathematical approach.

It will look very similar to a p-n junction, but not exactly identical to p-n junction. So, once we know the current voltage characteristics of Schottky barrier diode we can compare that quantitatively with a p-n junction diode and will compare which one is better for what application from the real world point of view. So, all these things will take up immediately in the next class ok.

Thank you for your time.