Fundamentals of Semiconductor Devices

Prof. Digbijoy N. Nath
Centre for Nano Science and Engineering
Indian Institute of Science, Bangalore

Lecture – 24
Schottky Junction Under Equilibrium

So, welcome back. What did we learned in the last lecture? What we learned was we had studied the Schottky junction between metal and a semiconductor. We also highlighted the differences between Schottky and ohmic type of contacts. What kind of characteristics you expect from a device, if you have a Schottky contact or versus an ohmic contact.

We had studied the band diagrams for aligning the Fermi level between metal and N-type semiconductor, metal and P-type semiconductor. And you know you I told you that for making a P-type semiconductor and ohmic contact to a P-type semiconductor, you will need a metal with a large work function, whereas for making an ohmic contacts with N-type, you might need a metal with lower work function.

So, the choice of work function can dictate, what kind of IV characteristics you are going to get. If you form an ohmic contact, you will get a linear IV. If you form a Schottky contact with a barrier, then you will get characteristic which is very similar to that of P-N junction diode like behavior, you will have a forward turn on, and then you will have a reverse leakages is very low, and eventually it will break down ok.

So, all these things we have learned, also I had highlighted in last to last lecture about the importance of Fermi and metal contact to semiconductor right. We have studied the depletion depth, the built in potential, the Schottky barrier, we had derived the many equations which are very similar to an abrupt one side at P-N junction essentially.

So, today we shall quickly finish the Schottky junction treatment by going through the derivation of current. What is the magnitude of current that flows through a Schottky junction, when you forward bias or reverse bias it. Once we know that, then we will be able to correlate with you know P-N junction and compare which device is better Schottky diode or P-N junction diode, and we will see what is the current magnitude in both cases for example ok. After that we will start with a new topic a real transistor called BJT or Bipolar Junction Transistor. So, before we start that, we will finish up the entire things that we need to do for Schottky junction, and compare it with P-N junction ok. So, we will come to the whiteboard.

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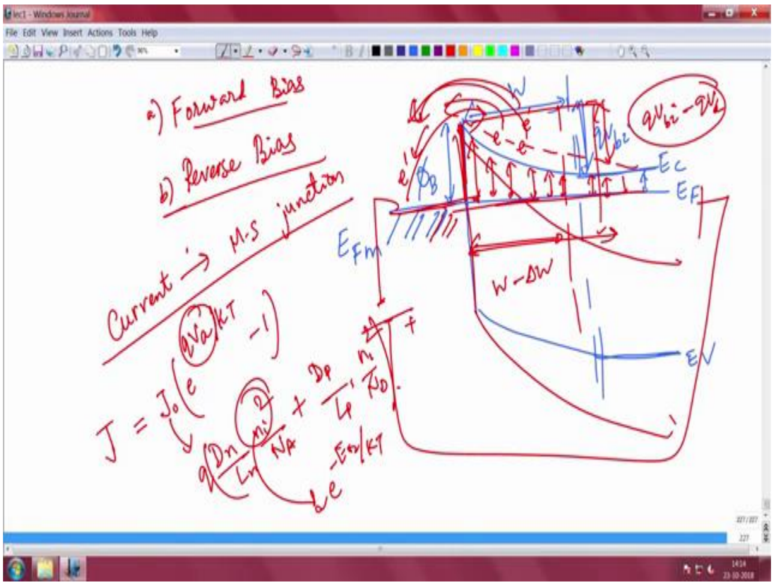

If you remember in the last class, we had derived the expression for the different parameters in a Schottky junction. You know if I draw this as the Fermi level of the metal, and then there is a Schottky barrier like this here. I had solved also numerical, if you remember right. This is conduction band, this is Fermi level, this is valence band. And of course, as you know this is the depletion width, and this is the built in potential, this is the Schottky barrier height, which is dictated you know by the built in potential plus this gap here ok.

Please remember that this region is flat; this is the flat, there is no neutral there is the neutral region. And the E_C - E_F is constant here, but it is not constant here that please remember that ok. And this is a Schottky junction type and N-type semiconductor, you might as well make an ohmic contact in N-type semiconductor by having the work function of the metal lower than the work function of the semiconductor you can make a ohmic type contact, but here we are talking about Schottky type contact right.

So, I told you whenever you apply forward bias whenever you apply a forward bias, it means you are applying a sort of a positive bias on the metal with respect to we are putting in positive bias with respect to the semiconductor, you are putting a positive bias in which case in a forward bias you know electrons from the semiconductor will be transporting over this barrier to the metal here. And you know this barrier height, this barrier will keep reducing by q V_{bi} - q V_a, and the depletion also will reduce by w - delta w just like a P-N junction, because the electrons are essentially coming over this barrier ok. So, it depends on the energy that you are supplying , also depends on the temperature by the way ok.

Similarly, when you have the reverse bias junction when you have reverse bias junction, then you are going to apply a negative bias in the metal with respect to the semiconductor. You are going to make the depletion width longer, and the barrier even larger like this the barrier will be larger. And electrons will be pushed from metal to semiconductors side, but this barrier height is there which is not going to change it bias. So, you will have very little current, very low leakage current, and until it breaks down, right.

So, the objective now is to determine the current to determine the magnitude of the current through the across the across the metal semiconductor junction M-S junction metal semiconductor junction. If you recall in a P-N junction ideal diode, the current density across the semiconductor P-N junction is given by J_o e to the power qV_a/kT - 1,

$$J = J_o\ (e^{\frac{qV_a}{kT}} \text{-1})$$

where it shows the applied voltage. And this J_o was something like q into Dn/ Ln *ni^2 this is N-type so, N_A you know plus D_p/ L_p ni^2 /* N_D.

$$J_o = q * (\frac{D_n * ni^2}{Ln * N_a} + \frac{D_p * ni^2}{Lp * N_d})$$

If you remember that right and this is ni^2 dependent on band gap, it was proportional e to the power minus E_G/ KT,

$$ni^2 = e^{\frac{-Eg}{kT}}$$

so all these things you remember right. So, the in case of metal semiconductor junction this treatment is a slight different, because there is no diffusion you know or drift diffusion sort of a hole electron minority a junction is not formed here. It is a junction formed between metal and the majority carrier, electrons are majority carrier, there is no minority carrier injection like electron hole. So, the treatment and analysis is slightly different ok.

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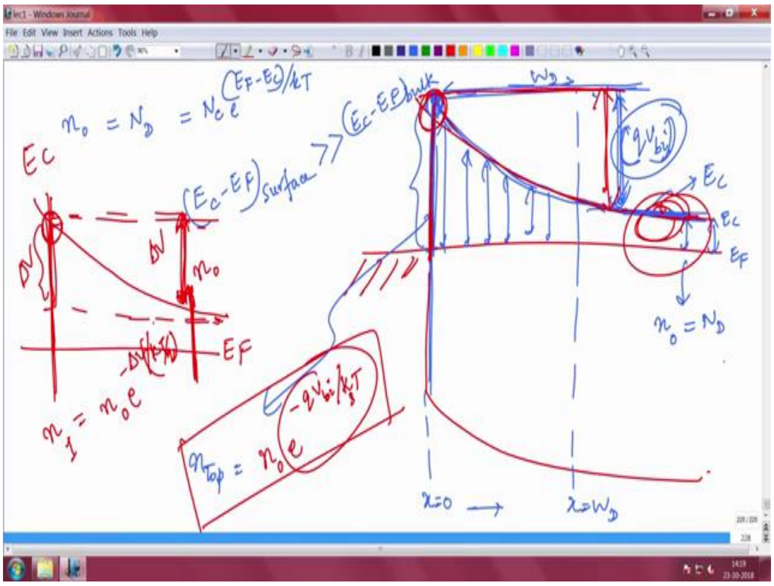

What I mean by that is that, let us take this junction and let us focus on this again ok. So, this is a Schottky junction ok. Now, let us do one thing first. This is the depletion, so am defining the depletion ok, this gap E_C - E_F that will dictate the equilibrium concentration here. Equilibrium concentration in the neutral region is n_o which is equal to N_D. And if you remember, n_o naught that is given by N_D that is given by the dense conduction band density of states exp $^{(EF - EC)/ kT}$ that is the equilibrium concentration that is constant from here to here ok.

Now, at this if I consider this as x= 0, and this is x-axis so this is x = W_D, this is the depletion region right. In equilibrium am talking about, so there is no light shining, there is no voltage am applying. At this point at x equal to 0, you see the conduction band is here the conduction band is here, the Fermi level is here. So, the difference between the conduction and Fermi level is huge.

So, of course the material is depleted and that is why, they are much fewer electrons at x = 0 here at this point here right, because the conduction band E_C - E_F at the surface. This is E_C - E_F at the surface, which is huge much larger than E_C - E_F at the bulk.

Bulk is deep inside the semiconductor here which is corresponding to equilibrium concentration, but this E_C - E_F gap progressively increases, it progressively increases right. So, at the surface it is the maximum here. So, the electron concentration at the surface would be the minimum, it is depleted there are very few electrons, but still will be few electrons compared to this part, but you know you will have some number ok, it is depleted.

So, if you look carefully, compared to this in a conduction band, this conduction band over here has an energy which is q Vi higher. So, this energy whatever you have conduction here, if you add that to this value, if you add that to this value, you get this particular conduction band.

So, in other words, this energy this energy is the excess conduction band that is bending the excess banding that has happened in the conduction band as it goes from bulk to the surface. So, if I say the electron density at this at this top is n_{top} that is the free electron concentration is depleted, very few electrons are there ok. If I call this as n_{top}, n_{top} is equal to the electron concentration at this point. If you recall a band, you know the electron concentration changes exponentially with respect to the band.

So, if the band has changed from you know this value to this value this particular gap, then the electron concentration here will be electron concentration here which is n_o times exponential of the negative of this exponential of negative of qV_{bi} /kT,

$$n_{top} = n_0 \exp(\frac{-q(V_{bi} - V_a)}{k_B T}),$$

please take a moment to look at this. I told you once that even if you have any profile like this of conduction band, and the Fermi level is suppose constant, then if at this point the electron concentration is n_o, and at this point the electron metal concentration is n_1, you look at the difference of the energy between these two points, this gap which is say delta V.

So, the electron concentration at this point will be lowered compared to the concentration here n_o by e to the power minus delta V/ kT that is that it goes exponentially as the variation in the energy band. So, this is the gap that has you know that is the extra gap that has arisen here right, this is the extra gap delta V that has arisen here, so and because the Fermi level has gotten that much far away.

So, basically the electrons concentration will decrease, where exponential of the amount that is why that is why, this here the electron concentration at the top will be electron concentration here times exponential of minus this ok. Why am I telling you all this, because we are going to derive the current expression. But, as of now we are only talking Vabout equilibrium, so how can you talk about current expression very good.

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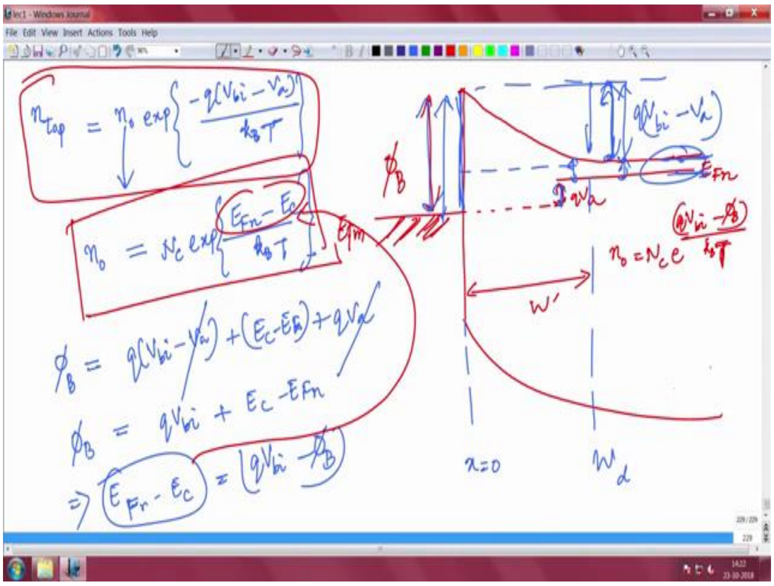

So, what you will do is that I will consider a small forward bias voltage that is applied. So, you know if we apply a small forward voltage, then there will be a small difference in the Fermi level. So, this is your metal Fermi level ok, and suppose this is your conduction this is a semiconductor Fermi level E_F this is a semiconductor Fermi level quasi Fermi level. So, this was the suppose the ϕ_B, this was the barrier that does not change at all ok, the barrier does not change.

And this has become like that, this has become like that, so you are bending has now reduced by $qV_{bi} - V_a$ that has reduced by that amount ok. So, there is a difference Fermi level between, this difference in a Fermi level here and here is actually q V_a that is the applied voltage we have given, the depletion length also has shrunk by some amount ok.

So, now at this is x = 0, and suppose this is the new depletion width W_d just talking about it ok. So, at this interface that x = 0, at this interface the electron concentration is n_{top} the electron concentration is n_{top}, which is given by electron concentration here which is n_o into exponential of what this gap which is now reduced because of application of a voltage. So, - q V_{bi} - V_a by this is Boltzmann time T all right.

So, now that is your electron concentration at the top ok. But, this n_o equilibrium here, of course there is equilibrium that is a far away in the bulk is given by N_C which is the conduction band density of states; exponential of what? $(E_F - E_c)/kT$

Now, if you look carefully this Schottky barrier height phi B is given by this which is $(q\ V_{bi} - V_a)$ plus this plus $(E_C - E_F)$ and plus this amount this plus this plus this will give you the whole Schottky barrier height, so that amount is qV_a. So, this qV_a get is qV_a gone, what remains here is $q\ V_{bi}$ plus $(E_C - E_F)$ n is equal to ϕ_B.

So, your $E_C - E_{Fn} - E_C = q\ V_{bi} - \phi_B$. Now, this value this value you can put it here right, so what will happen, then let us come to the next page.

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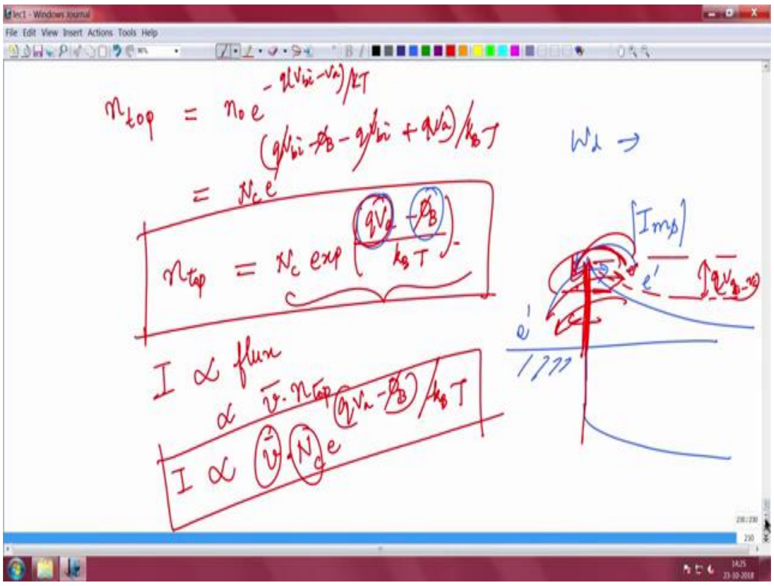

So, you can put or I can put right here only. So, if I write this equation now ok, so it will be n_o equal to N_c exp to the power instead of that I will put this $(qV_{bi} - \phi_B) / kT$;

built in voltage minus ϕ_B /kT this is T and this is c.

So, I can use this expression now. What will I write, I will write that as lets go to the next page. So, n_{top}, the electron concentration at the top is given by n_o into exponential of minus $V_{bi} - V_a$, so that is given by exponential $(-q\ V_{bi} - V_a)/kT$ right.

Instead of n_o what I will write is I write this V_{bi} - ϕ_B ok. So, I can write N_c exp to the power (qV_{bi} - ϕ_B) / kT. So, I will add this up also ($-qV_{bi}$ + qV_a)/ kT ok. So, this will go away. So, your n_{top} electron concentration at the top will be N_c exp (qV_a -ϕ_B)/k_BT.

$$n_{top} = N_c \exp\ (\frac{qV_a - \emptyset_B}{k_B T})$$

So, this is the way electron concentration in the top in the top, it is very small number, because your applied voltage is very small. Whereas, the built in the Schottky is pretty high, this quantity is very low actually, that why we call the film to be the top you know W_d to be almost depleted completely that is why, it is very low concentration.

Now, when you have a metal semiconductor junction in equilibrium- in equilibrium, the electrons tendency trying to come from here to here is exactly balanced by the electron tendency coming from here to there. We call that as say I metal the semiconductor current, which is basically the same from both sides it is balanced, and that is why there is no current flow in equilibrium. The moment you have non equilibrium you have applied positive forward voltage, it becomes low no it becomes low by that amount right by qV_{bi}- V_a right. So, electrons will now have a more tendency to come, so they can come now, so that is where this is coming.

Now, this current that will flow across this junction essentially that current if I write that current as I , that is actually proportional to the flux, the flux of carriers that will cross this. And the flux of the carriers depends on the velocity with which they are moving times the charge density. The charge density at this interface at x = 0 interfaces n_{top}.

So, in other words the current is proportional to the velocity of the electrons that are moving across this junction times the carrier concentration at this interface, which is N_c exp (qV_a - ϕ_B)/k_BT. This is your this is your current that is proportional here. And of course, there is a conduction band density of states here, this will be like a thermal velocity.

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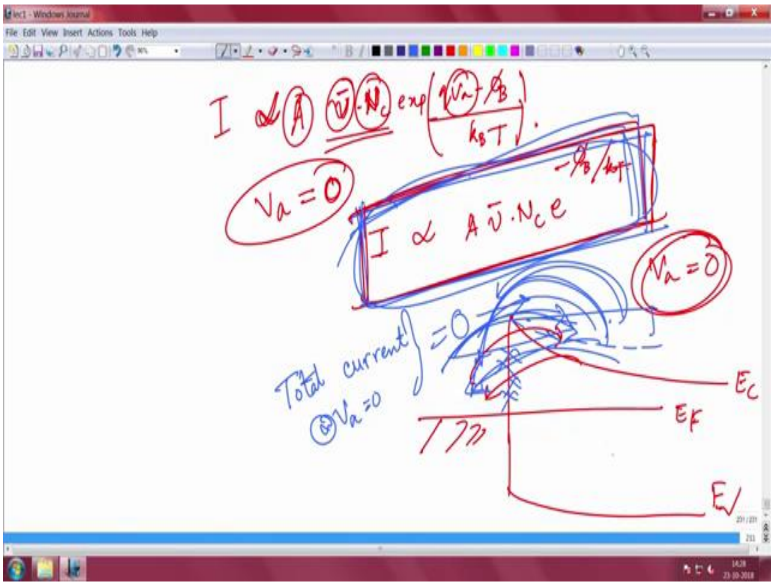

So, you can actually you know you can replace this from experiment with this proportionality constant that you have you know your velocity times N_c exp (qV_a - ϕ_B)/k_BT. ok. The proportionally constant can be actually obtained experimentally, and even some other more theories there. So, what you will club down the velocity, you will club down the density of states, it has a lot of temperature dependence this also has a lot of temperature dependence, so that way and of course they will depend on the area also; area of the current, the diode or the device so.

Eventually, it will look like A area into some constant call Richardson constant times T^2 exp (qV_a - ϕ_B) /k_BT ok, it will look like that.

Except that there is you know you have to subtract 1, do you know why that 1 has to be subtracted, I will come to that. There has to be actually this is not correct. Let me come to this a little later. So, there is a there is a proportion, I will come to that quickly.

So, there is a proportionality term here that will depend on many temperature and other things. So, you see this depends on the voltage applied V_a. If the voltage applied V_a is 0, then the current will be proportional to a velocity N_c exp power - $q\phi_B$ or q may not be there because this energy -ϕ_B/kT, you see this is the current that is there, when there is no applied voltage. But, we know that in a metal semiconductor junction, if there is no current, if there is no voltage, if there is no voltage that is applied which is you know Va = 0, then the total current across both side should be equivalent, so that is why it should be 0 ok.

So, when I say Va = 0, I get this current I mean that this current actually tries to go from both metal side to semiconductor side, and from semiconductor side to metal side, and they balance each other. So, the total current in the device at equilibrium at Va = 0 will also be 0. So, what is this current, this current actually is the magnitude of the current that tends to flow from metal to semiconductor, and from semiconductor metal balancing each other, resulting in net 0 current.

So, if I want to apply forward bias now if, I want to apply forward bias, then the for finding out the net current from semiconductor to the metal, the net electron flow from semiconductor to the metal will give you a current in this direction right. So, to find out the net magnitude of the current there, we have to subtract this current from the total forward bias current, see my point.

This current is basically the current that exists between the metal and semiconductor, and semiconductor metal that balance each other. And that is what the total current is 0. The moment you apply forward bias, and you reduce the barrier you know, when you have more now have current flow. The moment you apply forward bias that extra current what will the total current you get from that you have to subtract this current to get the actual true current flowing ok.

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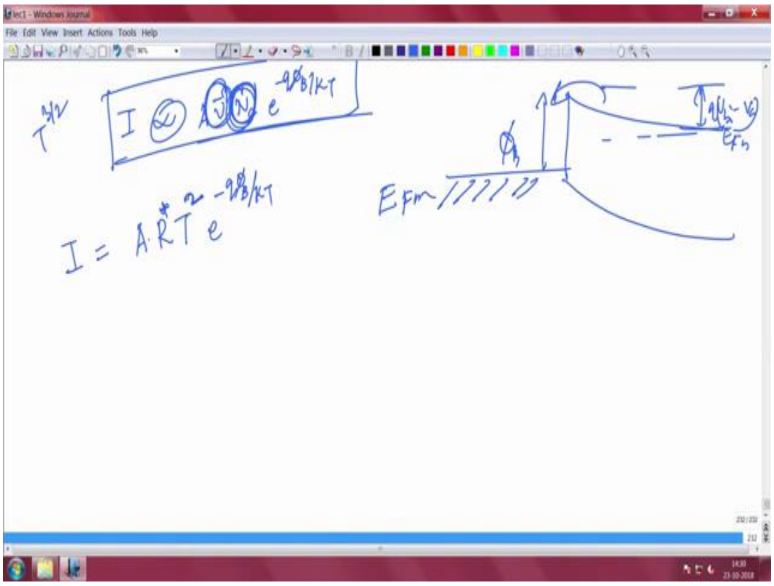

So, so what it means is that you know whenever you apply forward bias current whenever you apply forward bias, so you know the Fermi level will not be equal now. So, whenever you apply forward bias, so this is suppose the metal Fermi level ok, this is the Schottky barrier height. And this is the semiconductor Fermi level will quasi Fermi level, the barrier has reduced now right the barrier has reduced qV_{bi} - V_a right.

So, this quantity has to be subtracted, this quantity I which is proportional to area velocity Nc exp $^{(-q\phi_B/kT)}$. This component needs to be subtracted from the actual current, the current that should be flowing. Only then you will get the true current that is flowing right, because this is this is always there which is balanced actually ok.

$$I \propto A * v * \mathrm{Nc}\, e^{(\frac{-q\phi_B}{kT})}$$

So, the actual current under bias will be now this proportionally constant can be removed, I told you that is area times some constant called Richardson constant. And velocity and this all have their own their temperature dependence and other things. So, you can find out. So, this will be T^2 actually a temperature square dependency will come, because the conduction band density of states depends on $T^{3/2}$, velocity also has it is own dependence.

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So, it will be A R T^2 exp $^{(-q\phi_B/kT)}$. So, in total forward bias, you will have a term extra term you know that is exp$^{(qVa/kT)}$ that is why I applied bias minus this term you have to subtract A R T^2 exp $^{(-q\phi_B/kT)}$. As I keep as I had told you many times.

As I had told you many times, this term is basically the background term that has to be subtracted, because this is equal and opposite in the semiconductor metal junction this to this, and this to this is equivalent that is this ok. They balance each other, but the moment you apply forward bias more electrons will come here, so this current has to subtracted.

So, eventually the current will look like

$I=A\ R\ T^2 \exp^{(-q\phi_B/kT)} (e^{qVa / kT}-1)$

ok. And if you apply reverse bias, then this quantity will become negative e to the power negative quantity becomes very small quickly, so this quantity is almost becomes minus 1. So, this current will be the current, this component essentially this component will be the current that will keep flowing in the reverse bias. So, in the reverse bias in this is I, this is v in the reverse bias, the current that will be there is very small, and that current will be equal to this component ok. At 0 there is nothing at reverse bias this will be there, and eventually will breakdown.

In forward bias as we can see in forward bias, you can see that in the forward bias this is the total current which is exponentially dependent. So, exponentially dependence goes like this is 0 actually sorry just put here I V. So, this will break down is very small current. So, this is the forward bias characteristics ok, it is exponential increase just like a P-N junction.

Except that in P-N junction this is J_o in Schottky barrier junction this is this ok. So, this is a temperature also another dependence is T^2 here ok. So, you see in forward bias this regime, you have the exponential dependence in the reverse bias, you have a constant current given by this. Of course, there will be generation recombination current.

If you remember generation recombination current, whatever we did for P-N junction also will apply here, so it will slightly keep increasing here, because the generation recombination current also add some small component, but otherwise this component is your reverse bias component only ok. So, in reverse bias if the current should be constant and distribute a value from where you can actually find out phi B, if you know the temperature, but in reality its slightly increases.

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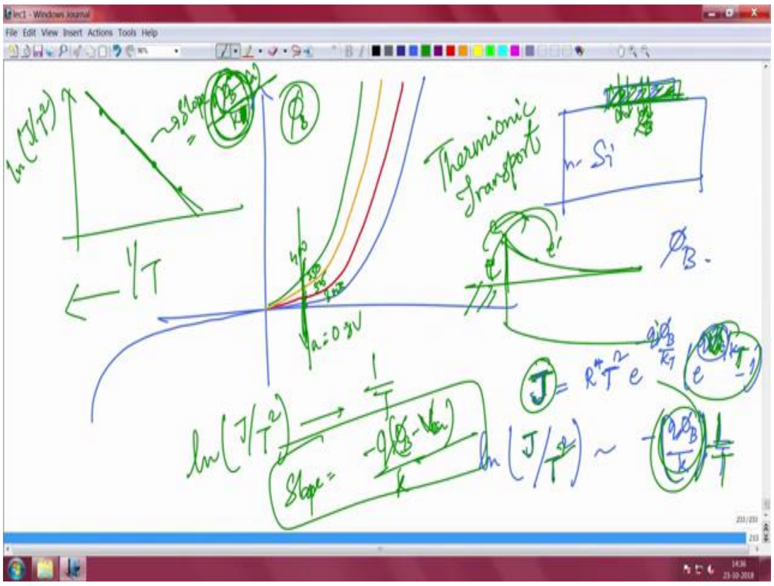

So, how do you find out you know one of the things that you find out from this temperature dependent, you know from this IV characteristics you that you know you are given a metal semiconductor junction. For example, you are given a metal semiconductors this is N-type, and this is suppose this is metal here. You are given metal semiconductor junction you are asked to find out the Schottky barrier height ϕ_B.

So, what you do is that you do the IV right you do the IV say this is room temperature ok, you recall the IV equation I equal to or the J current density. So, area is taken into account is some Richardson constant R T^2 exp $^{(-q\phi B/kT)}$ $(e^{qVa\,/\,kT}-1)$ ok.

So, if you take log of the current or current density versus T^2 , this T^2 you bring here, then it will be proportional to - ϕ_B/k into 1/T at a constant V_a. So, for example you take temperature dependent IV, suppose this is 300 kelvin, then you go to a slightly higher temperature. So, it will be something like that slightly more higher temperature it will be something like this you slightly go another higher temperature, you keep going like this right.

At any particular Va small Va, as say 0.8 volt or something at small Va, you look at the current here you look at the current, so that current is this J. You divide this is say 400 kelvin, this is 350 kelvin, this is 325 kelvin, this is 300 kelvin, it can take many temperatures,. so that current is that current at particular Va. So, you know the Va. So, you know this at different temperatures, you have you know this different current is there, you plot with respect to J/T^2.

And if you plot it with respect to 1/T, because this is the relation, then the you will get a slope like this. What am saying is that if you plot log of J/T^2 one by T, so it means temperature increasing this way. Then you will get this data points that fit like this, it will be a straight line. And the slope of the straight line will be minus this quantity q phi B by k T from there you can no actually T will not be there. So, minus q phi by K, so from there is no T here from minus q phi by k you can find out the Schottky barrier height phi B right.

Sometimes of course, you want to keep the Va also, so it will be minus V a like this. So, from there you can find out the slope. So, this kind of transport is called thermionic transport ok, the Schottky transport that is happening here is called thermionic transport, because it said you know it is an injection across the thermal barrier like the thermal injection is across a barrier. So, this is the conduction band, this is the valence band. Electrons are coming here electrons are coming here; this is a barrier the electrons are crossing purely because of thermal energy right. So, this is called thermionic transport.

And thermionic transport has this signature that log of the current verses T square. If you plot with respect to 1/T, the slope gives you minus $q\phi_B/k$, it can sometimes be $q\phi_B$ - V_a. So, you actually can you know V that is a particular Va you are looking at you know. So, basically from the slope we can find out the from the slope you can find out the barrier height.

So, this is a very fantastic way you are finding the if you make a metal contact to semiconductor, if you do temperature dependent IV, then you can find out the Schottky barrier height at the metal semiconductor interface. This is a very beautiful approach to finding the Schottky barrier height in a metal semiconductor junction.

And any new research that people do with different kind of materials carbon nanotubes are molybdenum disulphide, this new materials new structures. They always try to see if the if the transport you know the current voltage characteristics is it like a Schottky nature is it a thermionic. So, this signature gives you that it is a thermionic Schottky kind of a transport ok. And then you will be able to extract the barrier height. So, this is the beauty of this you know thing.

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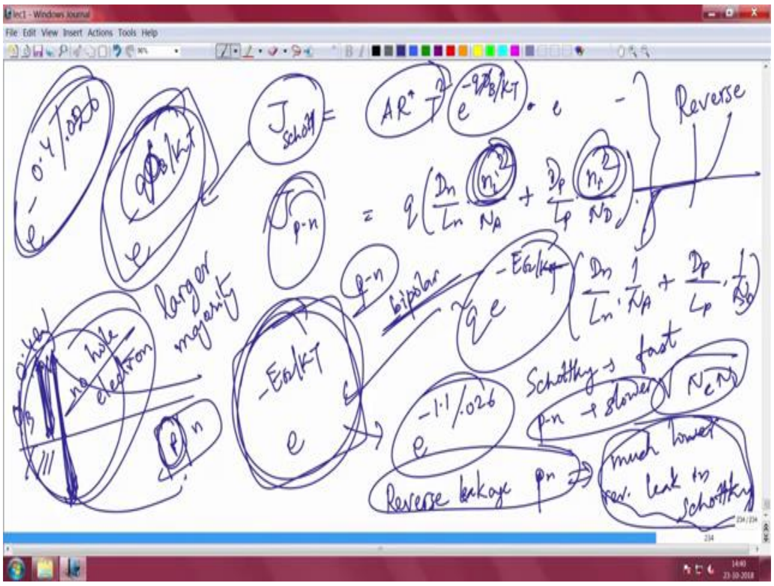

So, now we are pretty much finished up Schottky way of junction except that we have to take into account one small thing that you know the Schottky barrier total equation is given by

$$J_{schot} = exp^{(\frac{-q\phi_B}{kT})}(exp^{(\frac{qV_A}{kt})}\text{-}1)$$

this is a Schottky junction.

And at P-N junction this is given by

$$J_o = q * (\frac{D_n * ni^2}{Ln * N_a} + \frac{D_p * ni^2}{Lp * N_d})$$

So, this term is the same, rest all terms do not matter so much this exponential term that matters. So, here ni^2 is there that ni^2 actually can be written as

ni^2 = exp ($-E_G$/kT) right. So, I can take this also out q $exp^{(-Eg/kT)}$ D_n/L_n into 1/A plus D_p/L_p 1/ N_D. Of course, it ni^2 some other terms like square root of N c N v and all these things do not matter so much is exponential.

So, the Schottky barrier reverse current the reverse current, so I will erase this I will erase this ok. This is a reverse current in both Schottky barrier junction and P-N junction. You see in Schottky barrier junction reverse current depends $\exp^{(-q\phi B/kT)}$. So, more of Schottky barrier height lower is the leakage.

In P-N junction the reverse leakage depends as this which is $\exp^{(-E_G/kT)}$. Now, if you look into Schottky barrier junction this is Schottky barrier for example, this is your Schottky barrier phi B right. Your Schottky barrier this phi B is always less than the band gap you see, the band gap is much larger. Schottky barrier is very little is half of that maybe less than that compared to band gap.

So, this quantity will be always larger compared to this quantity, because $\exp^{(-E_G)}$. So, if I take silicon, this will that is what the P-N junction leakage will go as $\exp^{(-1/0.026)}$ that is the band gap, because this (Refer Time: 29:33) is there know. But, in a Schottky P-N junction to silicon it may be 0.4 e V for example, so that will Schottky barrier will give as $\exp^{(-0.4/0.026)}$. So, see $\exp^{(-.1)}$ will be always much smaller than this.

So, the reverse leakage the reverse leakage in P-N junction in P-N junction is always much lower than the reverse leakage in Schottky. Even if Schottky junction and P-N junction characteristics looks similar, which is you know it goes like that, but the reverse leakage in a P-N junction is much many orders of magnitude lower than the reverse leakage in a Schottky, because, in a reverse leakage in a P-N junction depends on the energy of the band gap $\exp^{(-E_G)}$.

But, in a Schottky barrier junction it depends on $\exp^{(-\phi_B)}$, which is the square the Schottky barrier height, and that is always less than the band gap. So, the leakage in a P-N junction is much lower. So, if you want to block more voltage, if you want a low leakage, if you want to have higher breakdown device, instead of Schottky you should go for P-N, because P-N will give you lower leakage.

However, a P-N junction has both electrons and holes. And whenever there are holes move slowly, because their mobility is much lower. But, in a Schottky junction like this there is no hole, it is purely electron which is majority electron is majority. So, Schottky junction is a majority carrier device, a Schottky junction is a majority carrier device, because there are no holes electrons to electron only.

Whereas, a P-N junction is not a majority carrier device, it is both majority minority like it is a bipolar device right, and because of the holes because of the holes things becomes slower. So, a Schottky diode because there is no hole to slow down can be very fast, you can switch on and off much faster than at P-N junction diode which could be slower than a Schottky diode, but P-N junction diode will give you a higher breakdown. So, you have to trade off whether you want more breakdown or you want to more speed, so it is an application based decision that you have to take into account, when you do P-N junction and Schottky junction ok.

So, with that we will conclude todays lecture, and will also conclude Schottky junction. So, today we had learned about all everything that there is there on Schottky junction. We have derived the current expression the current voltage characteristics, it just like a P-N junctions and accept that there is extra T^2 term. So, the thermionic transport has a log of J/T^2 verses 1/T gives you that slope a straight line whose slope is basically the barrier.

So, from that you can find out a Schottky barrier height. And I told you that because the Schottky leakage depends on exponential of barrier height minus barrier height. Whereas P-N junction leakage depends exponentially on minor band gap, and band gap is much larger than Schottky barrier height that is why, leakage in P-N junction reverse leakage in P-N junctions is always many order magnitude lower than the leakage in a Schottky junction of the same material. But, P-N junction will be slower than a Schottky junction, because you have both electrons and holes and holes tend to slow down the device.

A Schottky junction is majority carrier device, because there are no holes for example, if you make any contact to electron. It is a majority device, so it can be very fast, but its blocking capabilities would not be as good as P-N junction, it cannot have as higher breakdown as a P-N junction ok. So, with that we will conclude Schottky junction completely, we have covered P-N junction, we have covered so Schottky junction. We are completely ready to study the next topic; you know which would be transistors ok. So, we meet you in the next class with the topic of transistors.

Thank you.