Semiconductor Device Modelling and Simulation
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Lecture - 26
Schottky Junction

Hello, welcome to lecture number 26.

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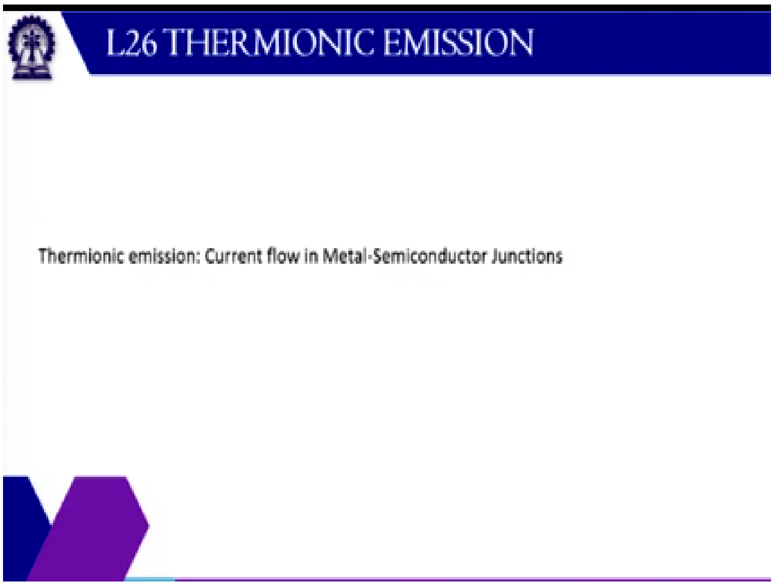

We will continue our discussion on metal semiconductor interface. So in this lecture we will discuss the current flow in metal semiconductor junction and that phenomena is called thermionic emission.

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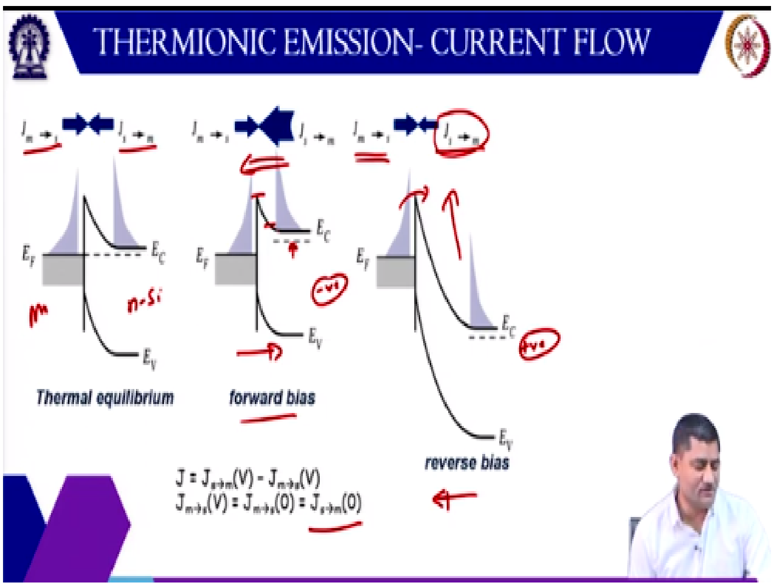

So let us look at the band diagram for metal and this is n-type semiconductor. So in equilibrium a no current can flow because we have not applied any voltage. So the current or these the flow of the electrons from metal to semiconductor will be equal to the flow of the electrons from semiconductor to metal and they will cancel out each other. When we apply the forward bias, so forward bias means this Fermi level will go up, because we have applied a negative voltage here.

So the energy will be minus q times v. So this will be positive, so this will go up. So now this barrier is less now. So this semiconductor to metal current or the flow of the electrons will increase. So that means, the current will be in this direction. Electron will, more electron will move from semiconductor to metal. In case of reverse bias, a positive voltage is applied here. So this barrier has increased.

So now less number of electron will go from semiconductor to metal side. And metal to semiconductor side that flow of carrier will remain same. So a small reverse bias current will flow in this direction. So this is the qualitative picture of metal semiconductor junction or thermionic emission current flow. Now let us estimate what will be the value of this current.

Another thing you can notice here, because this semiconductor metal flow will almost go to zero at high reverse bias. So this reverse saturation current is actually the flow of these carriers from metal to semiconductor or Jsm. So this is basically the reverse saturation current. So we can find out from the reverse bias current. And rest will be this reverse saturation current times exponential this barrier, exponential q V applied by kT. So something like this format of the current we should expect.

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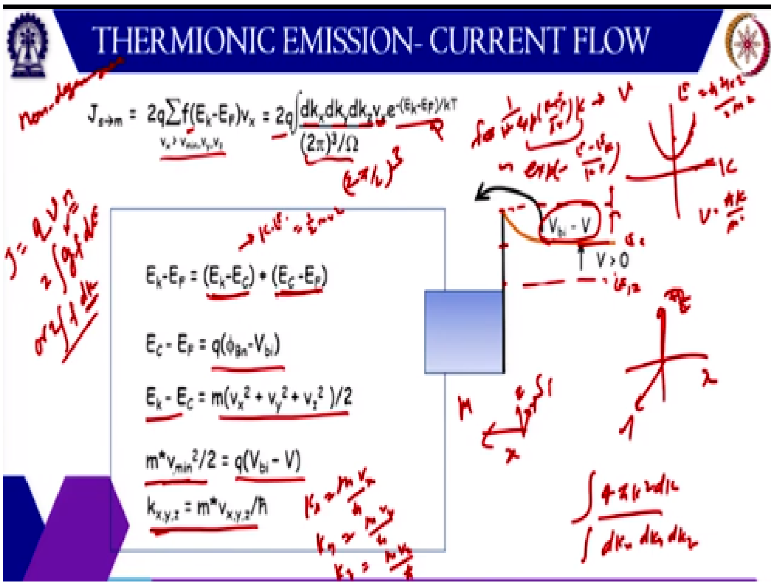

Now how do we estimate this current. So the current if you recall can be written as the charge on the electron times their velocity times the total number of carriers. So J is equal to u n times V. The number of carriers we can find out by integrating the density of state g times Fermi-Dirac distribution dE. So this will be n. Or you can also find out this by integrating f d k.

So this dk is basically, the dk will tell you about the states. So k is the states and if you integrate this dk over all 3d, you will get the total number of states basically. And each state has two electrons. So you will actually multiply this thing by 2. So overall expression you can see, so this can be 2 times f dk. So 2q f times V summed over all the values of the state.

Now please understand this state k is actually the velocity of electron because crystal allows certain velocities of electron in certain direction. So if you recall this EK diagram, so E is equal to h bar square k square by 2m m effective basically. So these are actually the velocities. So because velocity is h bar k by m. So for a given energy or for a given velocity there is a wave vector.

So wave vector is directly related to the velocity. So these are the states. So this electron can have the velocities falling on this curve. So when we integrate it over all these states, now this is a 3d. You know your semiconductor is a 3d material. So it can be in x direction it can be in y direction or it can be in z direction. So in all three directions these velocities are possible.

Now let us consider a metal semiconductor junction. So let us say this is your x direction. So rest y and z are in the plane basically. So they can be integrated over you know plus infinity to minus infinity because from plus to minus everything. But in case of x direction, this energy should be at least equal to this barrier height. And the barrier height is V bi - V. So what we do here?

This is 2q is same. Now V, V is the velocity, so V is here, V x. Now this current will be due to the carriers moving in x direction only, not in y direction or z direction. So we have only the V x component of the velocity. Now dk is in 3d. So this will be the volume of the k sphere. So while calculating the density of a state what we said, this decay in 3d was 4 pi k square dk integral.

So that was in 3d, but here we cannot do that. Because only the velocities in x direction which are more than certain having more than energy, q times V bi - V will contribute to the current. So what we will do, instead of writing 4 pi k square d square, we will write dk x dk y and dk z. So all three component. So this is the volume in k space. So that is what we have done here, dk x, dk y, dk z divided by the volume of individual state.

So that is 2 pi by L whole cube. So this is basically 2 pi by L whole cube. So this is the volume L cube which is given as omega here. Then this F is the Fermi-Dirac distribution. So if you recall f your f is 1 over 1 plus exponential E minus EF by kT. Now by using this expression we are assuming that semiconductor is non-degenerate.

That means, your Fermi level at least is away from the band f by at least 3 kT. So that means, this number is large, exponentially large. So this 1 can be ignored. So your f can be written as exponential minus E minus EF by kT. So this is what written here. So this is exponential E minus EF by kT. So this is minus sign here is there. Now this E k – E F can be written as E k - E c plus E c – E F.

Now why is that? Because E F is somewhere here. Now and E k are the values above this level. So E k – E F more than this will contribute towards the current flow. So from E F to this E c there is no carrier with this energy. So this is simply the potential energy. So what we have done we have separate this E c – E F component. Rest E k – E c is the kinetic energy. So that is half mv square.

So E k – E c is written as half mv square. So this energy can be, the velocity can be x direction, in y direction, in z direction. So v square is basically v x square plus v y square plus v z square. So this is the energy E k - E c. Now E c – E F can be taken out because this is independent of the other part. So E c – E F it can also be written as q phi B n minus V bi. V bi is the built in potential.

Now there is a requirement on v x because V bi can be from minus infinity to infinity, not an issue. For v x, it should be at least q V bi minus V equal to this barrier height. And of course, h bar k is the momentum, so mv is equal to h bar k. So for all three so for k x we can write m v x by h bar, k y can be written as m v y by h bar and similarly k z can written as m v z by h bar.

So with this equation, we can write the individual limits for this k x, k y and k z. So for k z it will be from minus infinity to infinity. For k y it will be from minus infinity to infinity and for k x will be from minimum k x concerning the V minimum to infinity.

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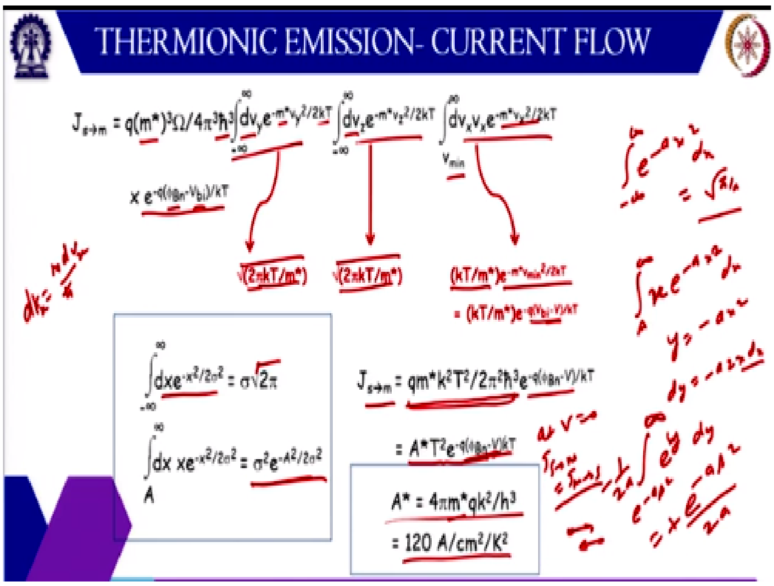

So these are the limits. And another thing you can notice here this E c – E F will be take out. E k – E c is half mv square. So we will combine v x with K x, v y with K y, v z with K z. So this is E c – E F that is taken out. And it is E c - E k. So half mv square. Then by kT, this kT is there, okay? Half mv square by kT. Then v x dv x. There is no component for v y and v z.

So we just have d V bi and d vz because dk is replaced mdv by h bar. Because k is mv by h bar so dk is mdv by h bar. So for kx it is mdv x by h bar. So m by h bar will come out. So it is m bar q by h bar q because there are three components x, y and z. And 2 pi by volume is taken here. So now we have to integrate these three terms concerning the v y, v z and v x. So all the kx are replaced by v x and all the ky and kz are replaced by v y and v z.

Now integrating these three terms for y and z, there is no issue it is from minus infinity to infinity. And if you recall a relationship e to the power minus a x square dx minus infinity to infinity is root pi by a. So here it is a form v square by 2 kT by m. So e to the power minus x square by 2 sigma square is sigma square root of 2 pi, because here a is if you compare with this one a is 1 over 2 sigma square.

So 1 by root a is root 2 sigma square. So sigma is taken out. So sigma root 2 pi. So this can be written as root 2 pi, sigma is kT by m. So 2 pi kT by m. This is also root 2 pi kT by m. For the x term, you have x here. So this can be understood like this. If you have integral x e to the power minus a x square dx, and the certain limit a to infinity. Here what you can do, you can replace this by y.

So let us say y is equal to minus ax square. So dy will be - a 2x dx. So this integral can be written as e to the power y and x dx can be written as dy divided by 2 a with minus sign. And the limit will be, at a it will be x equal to a it will be e to the power minus a times a square infinity it will be 0. X is 0 if a is positive this is 0. So this will be if you integrate e to the power y is integral e to the power y.

So this will be e to the power y which is –aA square divided by 2a minus so 0 is 1. So e to the, this is y is minus ax square. So this also infinity actually, this is infinity. E to the power minus infinity is 0. So this will be e to the power minus infinity will be 0. So this is 0 minus this. So minus minus will become plus. This is plus e to the power minus a square by 2a.

So this is if you write in terms of 1 by 2 sigma square it is written by 2 sigma square. Then you will get this expression. 1 by 2a sigma square times e to the power minus a square by 2 sigma square. Now a is v min here actually. So this can be written as kT by m times exponential minus m v minimum square by 2 kT. So m v minimum is half mv square is q times V bi - V.

So if you multiply all these three you will get pi B n minus V bi. Here you have V minus V bi. So this V bi will cancel. So what you will have? Phi B n minus V by kT. So phi B n is basically is a characteristic of the metal semiconductor junction. And other terms if you do the algebra, you will get this term.

So j current density from the semiconductor metal junction is qm k square T square by 2 pi square h bar q e to the power minus q phi B n minus V by kT. So this can be combined into one constant. So this is AT square exponential minus q phi B n minus V by kT. So A is called Richardson constant and its value it does not depend on the other parameters except the effective mass.

So this is around 120 ampere per centimeter square per Kelvin square. So this equation is also like a P-N junction diode equation. It is exponential qV by kT. Now this is the equation from one side. Other side equation basically, you will get for v very large reverse bias. So at v equal to 0 the current is basically 0. So if you substitute v equal to 0, you will get the equation of the current or the electron moving from metal to semiconductor.

So that will be obtained for v equal to 0 because they are equal basically. So at v equal to 0 this J sm is equal to J ms. So the total current density is basically the difference of the two. So electron moving from semiconductor to metal and metal to semiconductor, the difference of the two. So overall expression can be done as semiconductor to metal minus metal to semiconductor and that is same expression at v equal to 0. So we can take exponential qV by kT out and rest remain same.

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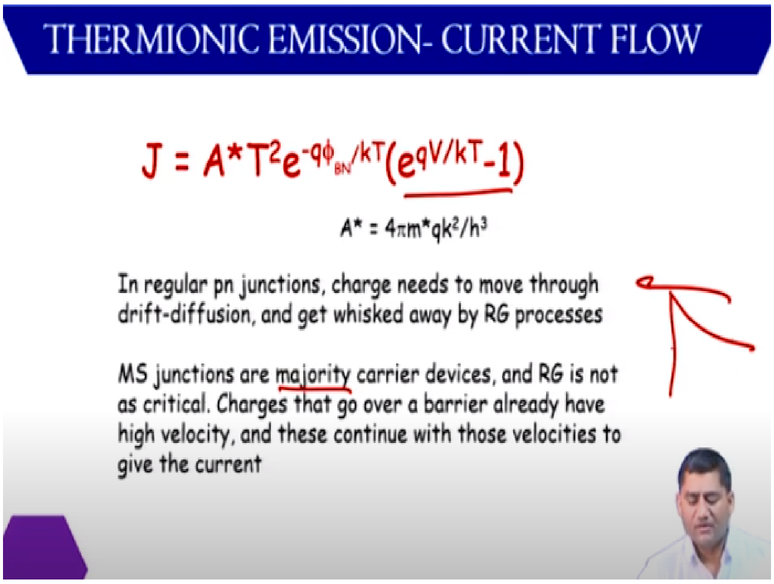

So exponential qV by kT - 1. So that will be the overall current density. Now if you notice the difference in regular pn junction charge moves through the drift-diffusion equation. So once it moves it diffuses and then there are generation recombination process in the other semiconductor. So the majority carrier slowly loses out. In metal semiconductor junction it is majority carrier dominated device.

So recombination generation is not that critical. Once charge crosses this barrier, it moves with the high velocity. And this gives you a better current characteristic, better transient characteristic, because you do not have to worry about the charge storage or the majority carrier charge.

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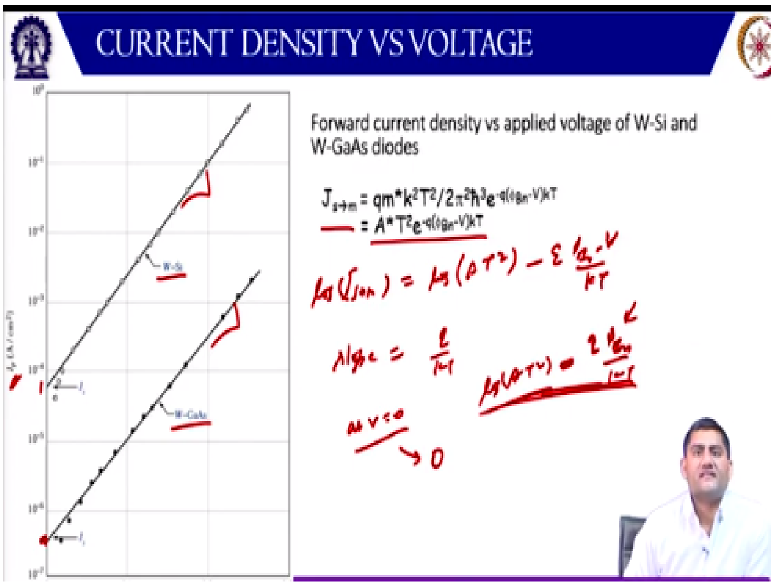

And if you plot this J versus the forward voltage, this is on log scale. So from the intercept, if you take the log of this thing, so log of J sm will be log of AT square minus q I Bn minus v by kT. So this at v equal to 0, so first you can get a slope. The slope will be q by kT with respect to v. And at v equal to 0 it will intercept as log of AT square is equal to q phi B n by kT.

So because AT score is a constant at a given temperature, so minus q phi B n by kT. So by the intercept at voltage equal to 0 you can find out the phi B and the barrier right. So this is I-V curve for tungsten silicon and tungsten gallium arsenite. So this will intercept the y axis the current through the metal semiconductor junction for a 0 bias. So now actual current will actually be 0.

So when you apply a 0 voltage the current will be 0. But if you extend the linear region here, this linear region if you extend, it will intersect at certain point and that will be given by this expression. So you can estimate the barrier potential from this I-V curve for the metal semiconductor junction.

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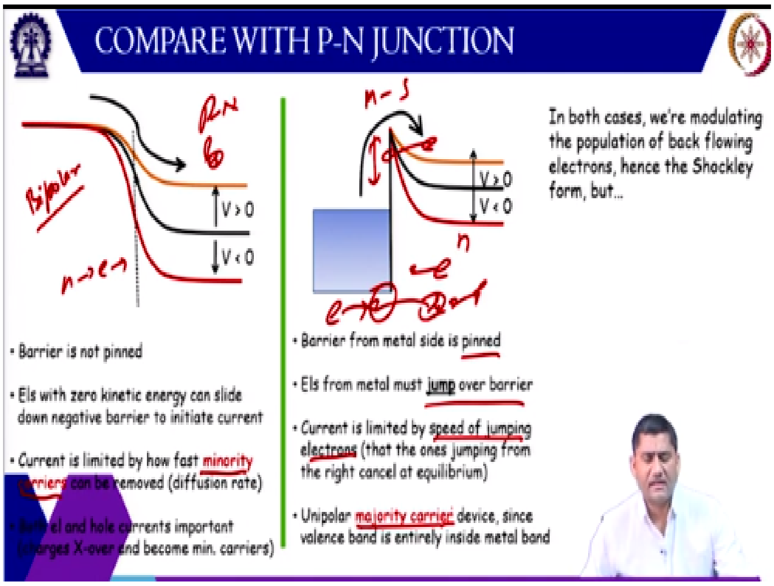

Now we compare the, this metal semiconductor junction with a pn junction. This is metal semiconductor junction. So here the barrier is in case of pn junction barrier height is not fixed unlike in case of metal because there is a phenomena called Fermi level pinning in metal semiconductor junction. So this site is fixed. In case of pn junction, the height from either side is not fixed. So both the barriers are same and they vary with the applied voltage.

Now barriers from electron must jump over the barrier from electron site and this is limited by the speed of jumping the electrons. So if they move with a high speed then this carriers will continue. And another thing you can notice here if this is n type then only electron will take part. If it is p type then holes will take part. So there is no question of having a minority carrier diffusion there.

Because this will send the carrier, the semiconductor will send the carriers. So it is the majority carrier device. In case of pn junction, this p type will send the holes and n type will send the electrons and they are minority carrier on the other side. But here on the metal there are only electrons no holes. So if it send the electron they contribute towards the electron here in the metal.

If it sends hole then what will happen it will combine with the electron. So that is one electron will come from the metal it will recombine at the interface itself. So usually this current in the case of pn junction is limited by the minority carrier lifetime. So how far these minority carriers can be removed. And both electron and hole current they are important, so both carriers.

So this here basically we call it bipolar, okay? So both the carriers are important in case of pn junction. In case of metal semiconductor junction it is only the majority carrier that are that play a critical role. So this is the brief comparison between the metal semiconductor and pn junction.

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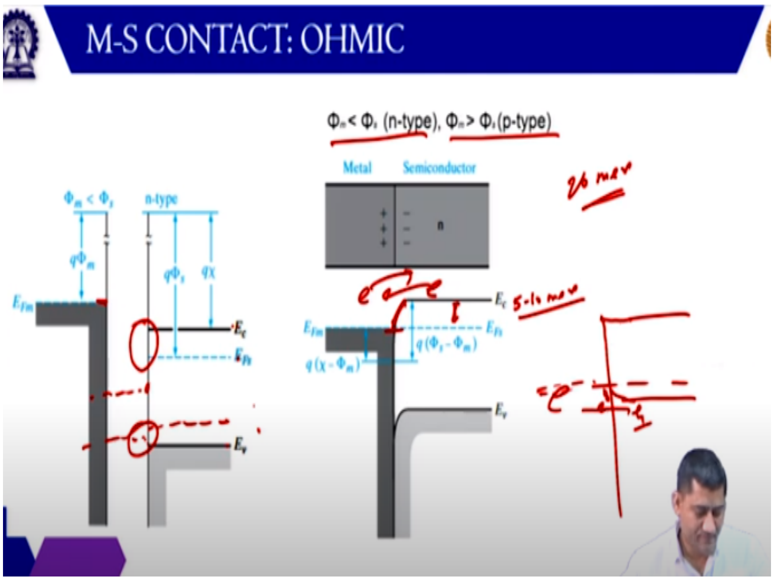

Now let us look at the metal semiconductor contact and when this contact will be ohmic. Ohmic contact means there should not be any barrier, okay? So let us say you consider a metal an n type semiconductor. If the Fermi level of metal is in between this E c and E F for the semiconductor, then it will be ohmic. When it is in this region, then the Fermi level will align and then accordingly this barrier will be very small.

So electron can easily move from the semiconductor to metal and electron from metal to semiconductor we will see a small barrier which is you know few millielectron volt. And at room temperature it is 26 millielectron voltage the thermal energy. So that is 26 millielectron volt. So if this barrier is only few electron volt let us say 5 to 10 millielectron volt, this barrier is insignificant because thermal energy is quite high enough.

So this barrier is actually will not play at all and the current flow will be you know same from both side. So this junction will not differentiate whether it is you know you are applying a positive voltage or negative voltage. So this is for n type. In case of p type the Fermi level is somewhere here. So now this metal Fermi level lies here for p type semiconductor.

Then this will be again a Ohmic contact. That means, if you draw this diagram, so this is somewhere here, somewhere here and now you see here these holes the metal Fermi level, so the semiconductor Fermi level will come down because this metal

Fermi level is somewhere here. So this will come down. So this will go down like this. So the holes actually do not see a barrier here.

And these holes will combine with this electron. So from the metal site it is the electrons, from the semiconductor side these are the holes. So from either side they are not seeing any barrier, because these electron can easily combine with these holes here and these holes can easily go here. And again the barrier here is quite small, it is less than this thermal energy.

So the contact will be ohmic. But if the metal Fermi level is somewhere here, then this barrier height will be quite large. And then it will have preferential treatment for different biases and then it will act as a rectifying contact. So when phi m is in between the E c and E fs for n type E f and E b for p type, then the contact is naturally ohmic. Now in other cases, how can we make it Ohmic contact?

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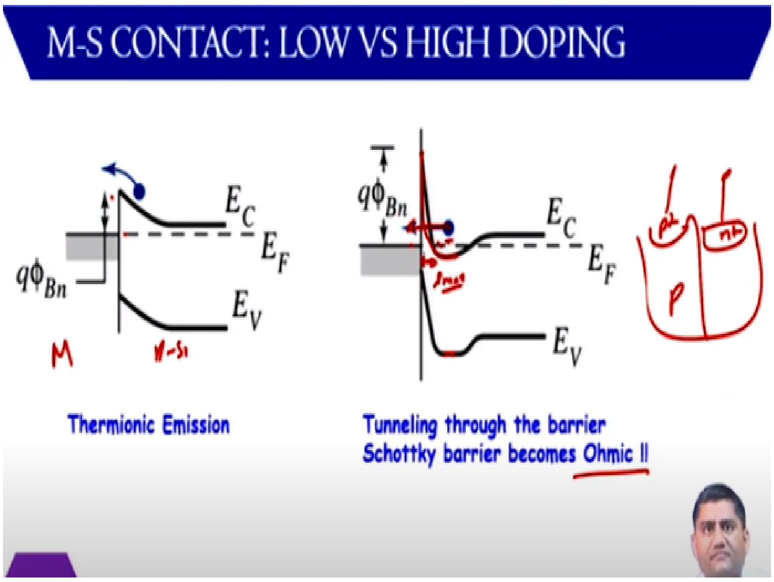

So what people do? They use high doping there. So let us say this is your n type semiconductor and this is the metal. And there is a barrier here. Now what we do? We dope it. We dope it high enough so that the Fermi level is in the conduction band. So if Fermi level is in the conduction band, then this Fermi level will align and this will be the band diagram here. So this will sharply go down here.

And because this is highly doped this distance or this thickness, the barrier thickness will be very small. So due to this small barrier thickness, these electron can easily tunnel through. So that means, this barrier becomes kind of transparent. So then electron can go through because this barrier is so thin. So then it will again act like a ohmic contact.

So for n type semiconductor generally if you look at the contact, so this n+ contact is made for the metal to connect or for p type semiconductor a p+ contact is made to connect with a metal so that it is ohmic contact. Similarly, in case of metal p type semiconductor high doping is used, so that the barrier on the valence band side is also very small like this.

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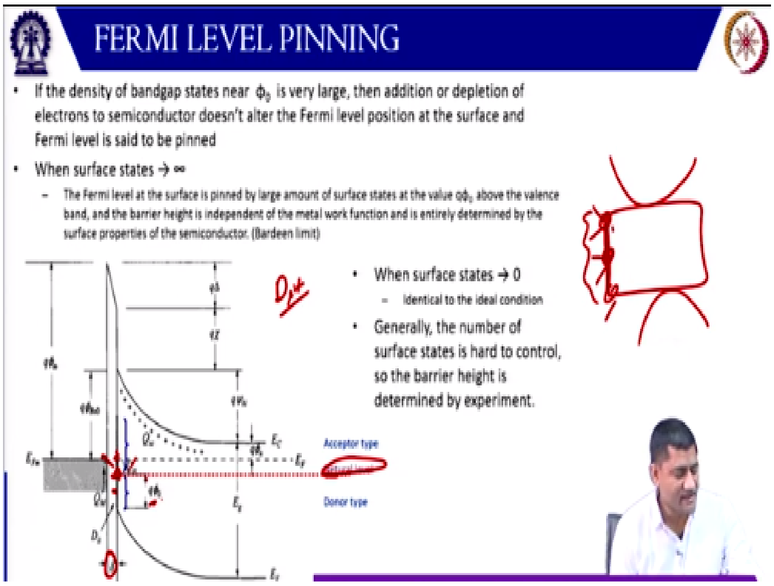

Now let us see in more detail, what is this Fermi level pinning. In case of bulk semiconductor, you can easily write the band diagram because there are no states in the middle of the band gap. So either the energy is allowed or the energy is not allowed. But at the surface, there are certain dangling bonds or these bonds are connected with some other material. So there can be states here in this region.

So at the surface energies inside the band gap are allowed. So we can say there are states with energy falling in the band gap region, because here it is not a full crystal. Here it is the interface state. So these interface states can take the electron that means electrons are allowed to have the energies in this region. So these are the interface states. Now it depends on what is the density of those states.

So let us say D i t is the density of interface states at that semiconductor interface. So what will happen? You can say that there is a small layer is getting formed there, where these electrons can come here to the states. And now these states will have certain neutral level. So if Fermi level is somewhere here, then it is neutral. That means there is no, they are not positive or negative, they are neutral basically.

And if above these states are filled, then it has acceptor type nature. So it has accepted the electron so it become negative. Then if it is below it, that is donor type. That means it has given the electron. If the density of states is very large, then the Fermi level will be pinned here. So Fermi level will not move from this level, this q phi naught level. If the density of state is 0, then the Fermi level will not be pinned, it will be given by the phi ms.

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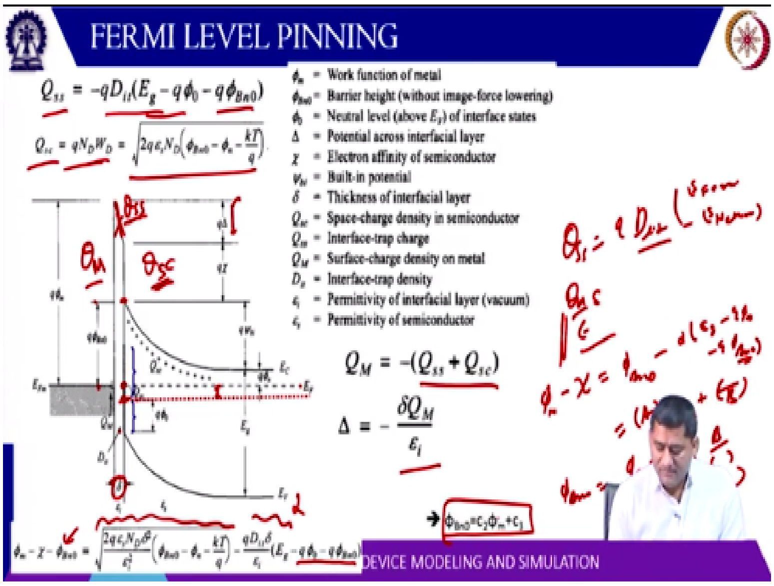

So in terms of charge, we can express it as there is a charge in the semiconductor region, there is a charge in the metal region. So this is semiconductor, this is the metal. And this metal charge, there are two charges here basically, one is at the semiconductor surface and these two charge will make up the, or they will be equal to the charge on the metal side.

So semiconductor charge is simple that is given by qN D times W, W is the depletion width. So this expression is well known. Now this surface charge is given by the q times D i t the density of states times the energy gap. So now we can write this one because we are assuming this density of state is constant.

So if it were not constant or it has it was varying with the energy then we will have to use the exact expression. So let us assume that this is constant D i t is the density of states at the interface. So D i t times the energy of Fermi level that is energy of the Fermi level minus the energy of neutral level. So that is the, so Fermi level is somewhere here and neutral level is the set q phi naught.

So the difference between these two will be if you take from here this is q phi m or if you take from this band h then this is, this depth is E g minus q phi. So E g is down here minus q phi. So this is the depth of this neutral level. Then the depth of this Fermi level is q pi B n, so minus q phi B n. So this is basically the difference between these two, so this difference times D i t is the charge in the interface state.

So this both the charts are electron charge, so you can write q N D W D and q this thing. So q M will be minus of Q ss plus Q sc, so semiconductor charge and semiconductor surface charge. And let us say this charge is on the metal side and there is a small interface layer you know atomic layer you can say, over this this is spreading. So the field will be if you have seat of charge Q m, then electric field Q m by epsilon.

And if it is over a distance delta, then there is a potential drop. So Q m times delta by epsilon i is this potential drop, is this potential drop here. And then the rest of the potential drop across this inside the semiconductor depletion region. So overall potential drop that is phi a minus chi minus phi B n. So phi m minus chi is this minus phi B n, this is the drop.

So this can be written as phi m minus chi minus phi B n is equal to delta Q m by epsilon. So delta by epsilon times Q m. So Q m is Q ss plus Q sa. Now if you estimate that this term under the bracket is usually quite small. So and so we ignore it. Then we have this Q phi naught minus Q phi B n minus E g.

So by rearrangement you can write it like this is phi m, so let us write phi m minus chi is equal to phi B n naught. We have taken to right side this phi B n term on right side.

Then let us ignore this square root part and this is some coefficient, let us say alpha. So this minus alpha times E g minus q phi naught minus q phi B n naught, okay?

So this is something phi B n is taken here, so some coefficient times phi A B n naught and plus other terms. So your phi B n naught can be written as phi m minus chi by this thing. And then let us say this is A this is B, minus B by same thing. So this phi B n naught is proportional to phi m. And then some constant depending on this chi and other constant.

So phi B n naught can be written as a constant times phi m plus another constant. So this is precisely the barrier height. Now earlier we said when there is no interface state, we said c 2 is 1. So phi B n was simply phi ms. Now for a semiconductor when we include the interface states, then we get this expression.

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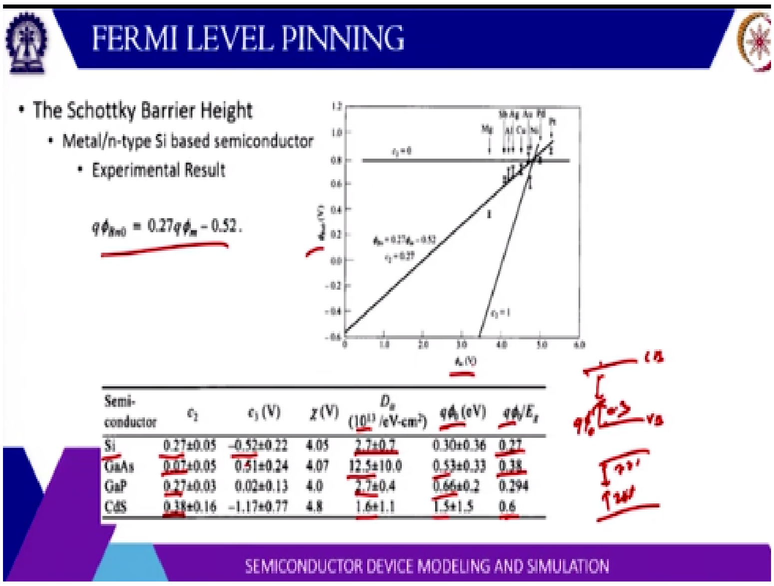

And from this we can say that for different semiconductor, if they have more density of states at the interface, then (()) (36:29) will be less basically. So it will deviate from 1. For ideal it is 1 and if this interface states are there it will be less than 1. So let us compare this thing for couple of materials listed here. For silicon c 2 is around 0.27 and c 3 is around -0.53.

So that tells you that density of a state is around 2.7 into 10 raised to the power 13 per electron volt centimeter square. For gallium arsenide this is 0.07. That means it is almost constant. So that means density of state should be even larger. So you see here it is around 12.5 into 10 raised to the power 13. Then for gallium phosphide is 0.27. So here similar density of state as the silicon.

For CdS it is even more close to ideal. So the density of state is even less. So 1.6 into 10 raised to power 13 per electron volt centimeter square. And of course, by comparing this thing you can find out the neutral level. So in silicon it is around 0.3 from the valence band h. In case of gallium arsenide it is around 0.53 from the valence band h. For gallium phosphide is around 0.66 and CdS around 1.5 electron volt from the valence band h.

So this is q phi naught from the valence band h. And of course, if you take the ratio q phi naught by E g. So in silicon it is around 0.2. So this is 1, the band gap is 1, it is at the height of 0.27. So from if this is let us say at 27% height. So this below me it is 77% below. So this is around 38% so gallium arsenide. So somewhere you know slightly below the middle point and it is above the middle point in case of CdS.

So this is the equation for silicon. So this is the barrier height versus metal work function for these materials. So we have completed our discussion on current flow and the Fermi-level pinning in metal semiconductor junctions. Next we will discuss about the field-effect transistors. Thank you very much.