Processing of Semiconducting Materials
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Lecture - 30
Metal Semiconductor Contact – II

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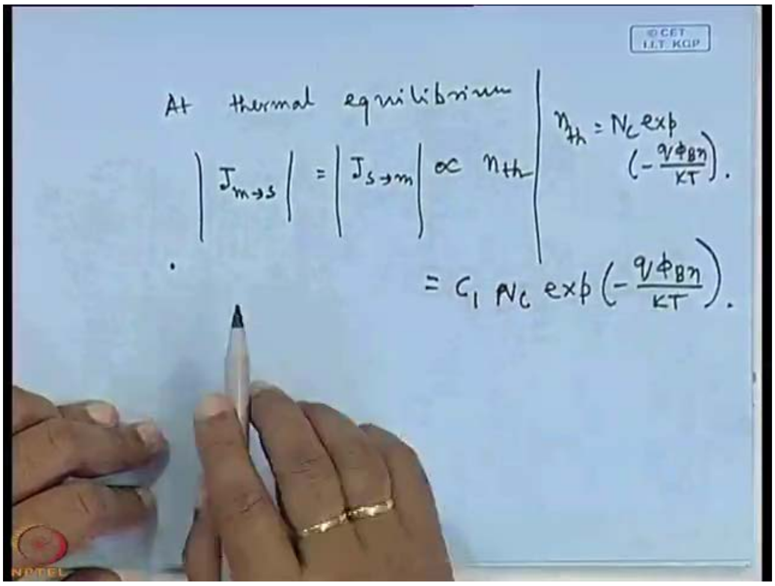

At thermal equilibrium, current density from metal to semi-conductor is equals to current density from semi-conductor to metal. That must be proportional to the number of electrons thermionically emitted. I am taking the mode, because the sign may be different. It may be negative. It may be positive. So, at thermal equilibrium means you see that we have started from this thing n t h is equals to N c exponential minus q phi B n by K T. This we have seen in case of the, it is the electron density for the thermionically emitted electrons, thermionic emission that is the electron current density.

Now, this is the current density at thermal equilibrium, which means there will be two things. One is from metal to semiconductor or from semi conductor to metal. That current density must be proportional to the number of electrons thermionically emitted from the semi-conductor to the metal. Now, when a forward current that means we can write that this is equals to c 1 N c exponential minus q phi B n by K T. Why there is c 1 constant? This is constant of proportionality. So, it is a thermal equilibrium.

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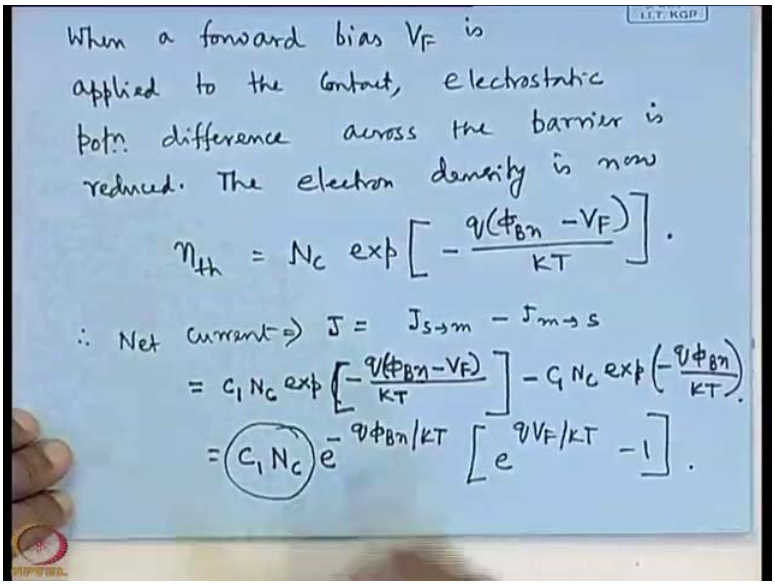

Now, when a forward current, when a forward bias V F is applied to the contact; electro static potential difference across the barrier is reduced. Now, the electron density is how much? It is the same thing n t h is equals to N c exponential minus q phi B n minus V F by K T. You agree N c exponential minus q phi B n minus V F by K T. This V F is the forward bias, which in which is lowering built in potential. Now, if you apply a reverse bias suppose V R, then what should be the expression? It should be plus. Yes, it should be phi B n plus V R, phi B n plus phi V R. You see that.

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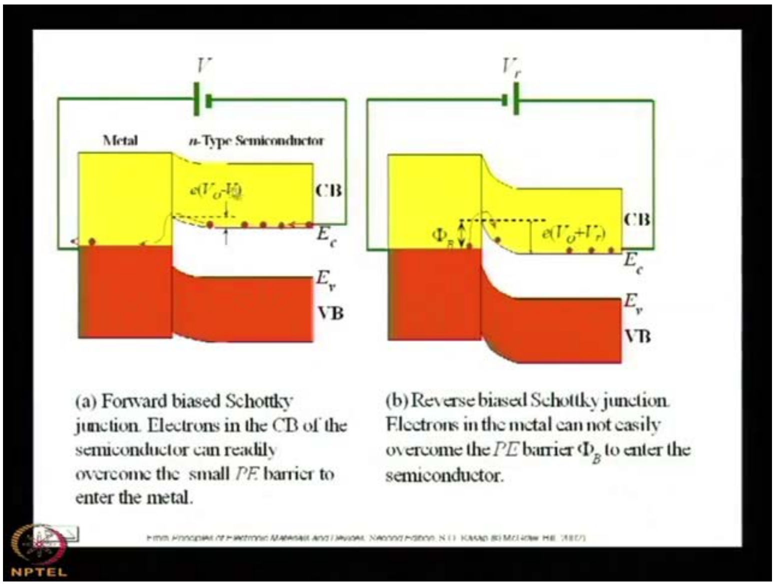

If you see this view graph that means this is the positive potential, which is being subtracted from the built in potential. That means on application or positive voltage, it is reducing. On application of reverse voltage, it is increasing.

Student: Sir.

Yes.

Student: As in the case of Schottky diodes?

Yes. The depletion region is electrically neutral.

Student: Depletion region.

Is electrically neutral or not?

No no no no, electrically neutral will be there to as a whole.

Student: Whole system?

Yes, the whole system it will be electrically neutral. But, there will an electric field here.

Student: There are positive ions.

Yes, there are positive ions.

So, how do you maintain?

Total system it is conserved, but so far as the depletion region if you consider separately then it is not maintained because on the depletion region only positively charged.

Student: Yes sir.

Ions are there, so it is not maintained.

Student: Sir, gradients of ions will be there.

Yes, gradients of ions will be there.

Gradients of ions will be there because not that it is constant there will be with distance it is increasing basically if you if you go from x equals to 0 to the bulk from x is equals to 0 that means contact to the bulk it is increasing. In case of this, we are making it defectively neutral. Yeah.

But, in that case, it is not there? It is it is not there. Now, it has some applications also. In my next class, probably on Thursday, I shall show you that how a Schottky junction solar cell is built out of this principle, how a photo detector is built out of this principle. They are very efficient and very simple. Now, the electron density is this. Therefore, net current J is equals to J semiconductor to metal minus J metal to semiconductor. This is equals to c 1 N c exponential minus q phi B n by K T minus V F minus c 1 N c exponential minus q phi B n by K T. So, this is the net current. That means you are applying a forward bias.

So, the current is becomes this, which will be subtracted from that thing. This is equals to c 1 N c e to the power minus q phi B n by K T into e to the power q V F by K T minus 1. So, that is the net current. This is this c 1 N c. This c 1 N c is a coefficient coefficient.

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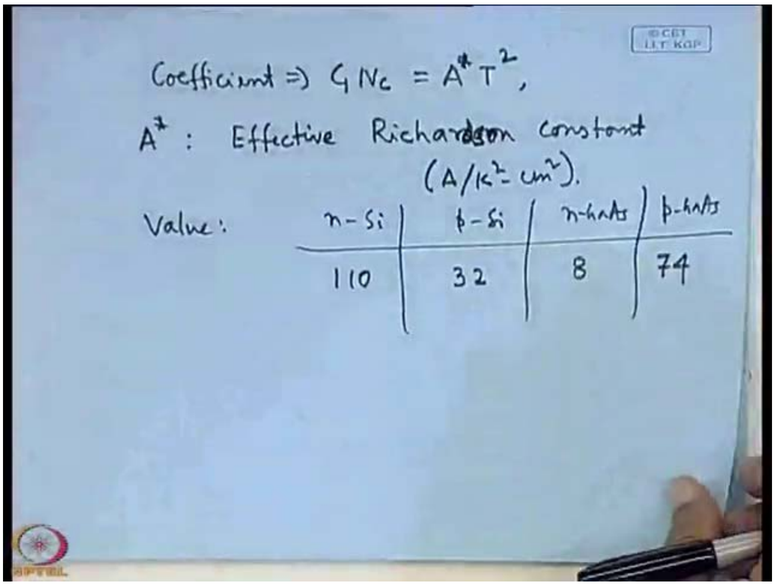

c 1 N c is known as A star T square, where A star is known as the effective Richardson constant, effective Richardson constant. Its unit is ampere per Kelvin square centimetre square. The unit of Richardson constant depends on the effective mass. What is the value of this A star? Value of a star is value 4 phi.

No, its value is for n type silicon p type silicon, n type gallium arsenide and p type gallium arsenide. There are 4 cases we will encounter. This is 110 for n type, 32 for p type, 8 for n gallium arsenide and 74 for p gallium arsenide. The unit is a per Kelvin square centimetre square. These are the values for the effective Richardson constant, though the value will be given in the numerical problem. It will be given. Now, you see that this is the net current.

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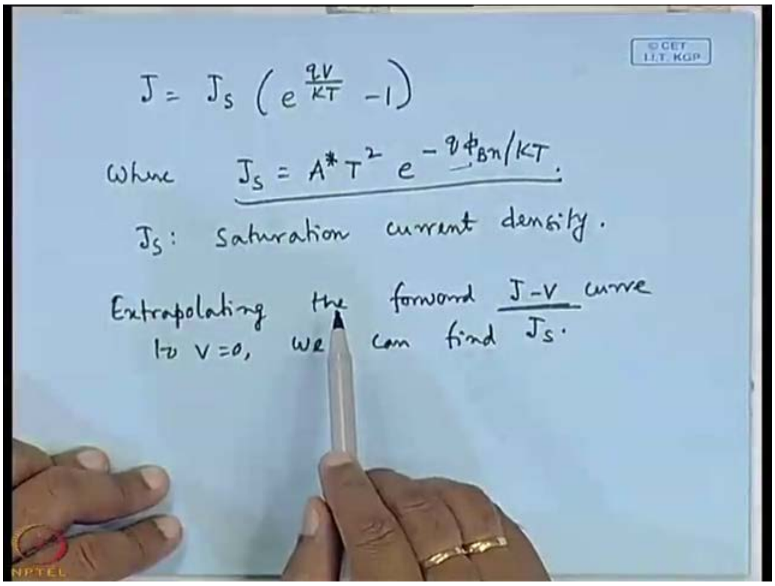

If I write down the net current, I can consider this to be J s or the saturation current. This is J s, which is not the saturation current. So, net current J can be equals to J s e to the power q V by K T minus 1 where J s is equals to A star t square e to the power minus q phi B n by K T. J s is known as saturation current density.

Now, in this expression, if it is forward bias, it will be positive. V will be positive. If it is reversed bias, V will be negative. So, this is the expression for the current density for a metal semiconductor Schottky junction, metal semiconductor Schottky junction. Now, what you see from this expression? You see from the expression that if you know the reverse saturation current, you can calculate barrier a barrier height.

Barrier height phi B n is calculated. It can be determined if you know the J s. Now, how it is known? It is known from the I V characteristics or the J V characteristics, J V characteristics extrapolating the forward J V curve to V equals to 0, we can find J s. That means you are in a position to determine the barrier height from the I V characteristics. J

V curve means it is nothing but the I V characteristics. I am not using here the I V because here the expression is in terms of J.

So, you have to divide by the area of the contact. It can be say 0.1 millimetres square. If it is a very small dot of gold on silicon or say very small dot of aluminium on silicon, then the area of the dot is the area of the device effective area of the device. It can be say 0.1 millimetres square, 1 millimetre square and 0.01 millimetres square. You can measure that thing. So, once you measure this thing, you can calculate the phi B n from the value. Now, you can, I can show you that this is the forward current versus the voltage.

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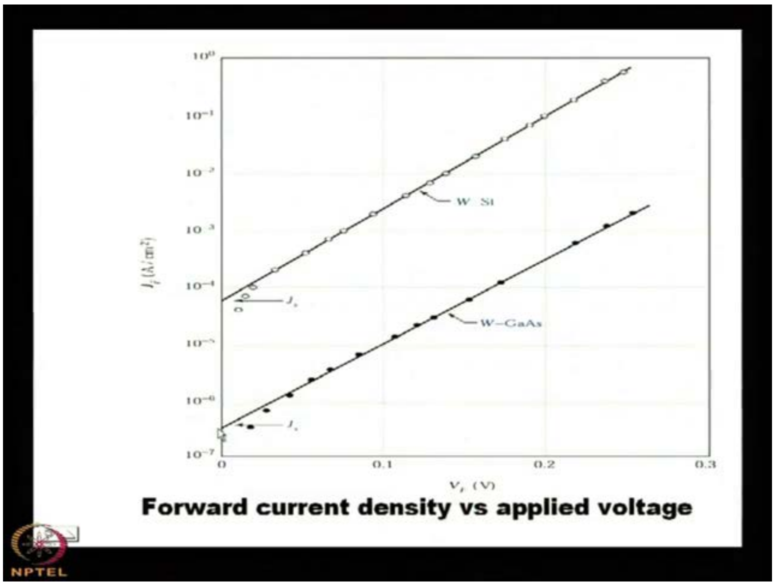

It is forward biasing. You would see for 2 cases. One is silicon on silicon where tungsten is, tungsten contact is made here. The same tungsten constant contact is made on gallium arsenide. You see that it is seen by this arrow. The value of the J s, the J s can be measured from the extrapolating the J v curve to V equals to 0. This axis V is on this axis. V is 0. So, extrapolating this curve to V axis will give you the value of J s. Once you know the J s, you can calculate the barrier height.

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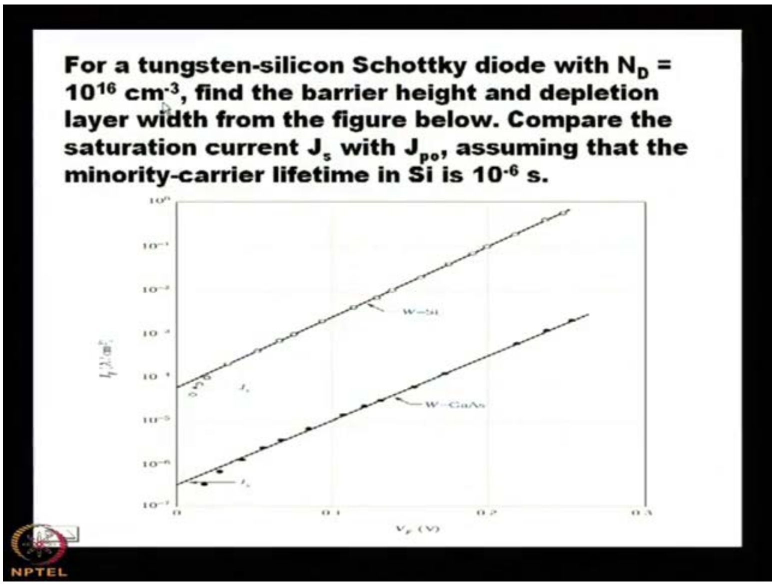

Yes, let us take this example for a tungsten silicon Schottky diode with N d equals to 10 to the power 16 centimetre cube inverse. Find the barrier height and depletion layer with from the figure below. Just you calculate the barrier height. That is all. You need not to calculate any other thing depletion layer with or comparison. That is not required because we have not completed the whole discussion. For time being, you just calculate the barrier height from this curve. It is tungsten silicon Schottky diode with N d equals to 10 to the power 16. So, what you need actually A star. You know tungsten silicon. What is A star? What is the value of A star? I have given.

No, A star is not for tungsten or anything. It is for silicon.

Student: 110.

T is how much?

Student: 300 Kelvin.

300 Kelvin.

q, you know or it can be in electron volt. The result will be in electron volt K T at room temperature is 26 milli electron volt or 0.26 electron volt. So, then you can calculate phi B n. Then, you can calculate phi B n. You calculate. How the phi B n can be calculated?

Student: Sir, J s is situation current?

Yes.

What is that? This current, I have shown you that it is basically the current at 0 biasing. At 0 biasing, I equals to I 0 e to the power e V by K T. When V is equals to 0 and I equals to I 0? I think before breakdown. No, normally, saturation current is the current, then it suddenly increases before breakdown. It just increases otherwise it remains constant. That is why, it is known as saturation. You see that this phi B n equals to K T l n A star T square by how much J s? This expression, this expression J s by A star T square, then take log of both sides. You will get phi B.

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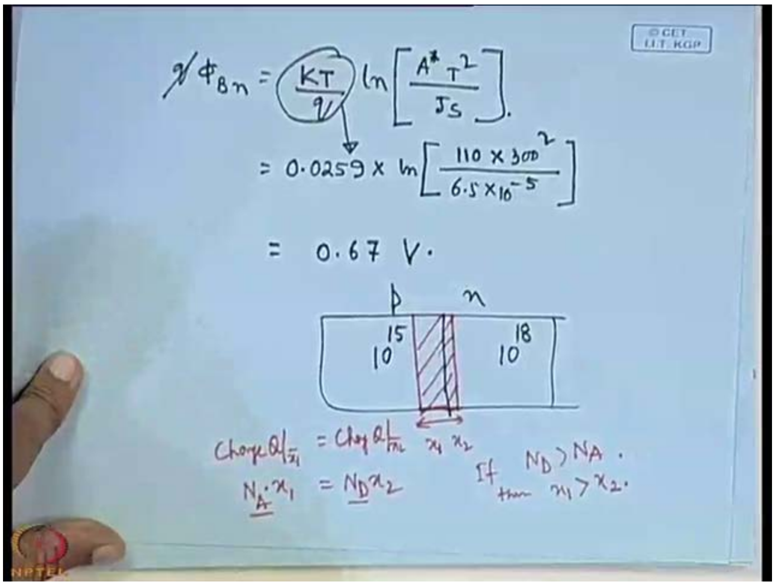

N equals to K T l n A star T square by J s. What is K T? KT is 0.0259 electron volt multiplied by l n. What is A star? 110 T square is 300 square by J s. What is the value of J s? You see that for silicon here, it is the value of the J s. The value of the J s is, it is the value of J s. It is equals to 6.5 into 10 to the power minus 5. Please write down the value. 6.5 into 10 to that power minus 5. 6.5 into 10 to the power minus 5 ampere per centimetre square obviously here. So, that will give you 0.67 volt. So, barrier height can be calculated from the I V characteristics. This is 0.67 electron volt. So, if you know the J V or the I V characteristics, you can calculate the barrier height from the I V measurements.

Any question on this?

0.67, 0.67 volt; if you multiply by q, then it will be electron volt. If you, if you want to tell in the electron volt, then you have to tell that it is q into phi B n.

K T we have taken.

Student: K t is in? Electron volt.

Electron volt, right.

No, no better.

The value of K T is in volt.

Student: K T by q is electron volt.

No.

See actually, actually, it is this thing. Then, this q goes to here. Then, K T by q becomes this thing in volt. K T by q. Then, it is volt. Clear? Yes. It is in volt. Now, we shall consider the case of c V measurements. It is from I V. Now, from c V measurements, we shall consider. What is the value of the barrier height? That is very interesting also. You see that when the metal semiconductor junction is made, the depletion width will extend inside the semiconductor region.

Why the depletion region will will extend inside the semiconductor region? No, it is because say, for p n junction let us, it is a p n junction. The depletion width layer will depend on the carrier concentration on both the sides. Suppose, the carrier concentration here is 10 to the power 15. It is 10 to the power 18. Carrier concentration is 10 to the power 15 on the p side and 10 to the power 18 on the n side. Then, how the depletion layer width will look like? It will look like this thing. It is on p side. It is more on the p side why. Low doping. Because of the... Low doping.

Low doping; because of the low doping. Basically, the total charges will be same on both the sides distance the product between the distance and the number of charges. Means number of carrier diffuse in will be the same. Not here the diffusion is same here the uncompensated charges here because in the depletion region there is no carrier. Only the uncompensated ions are there.

Yes.

Here, in the n side is more. So, the probability of transporting from n to p side is more. So, more uncompensated or charge particle should be there in n side more. No no no no. Actually, there will here say this is x 1 say and this is x 2 say. x 1 will be x 2 multiplication, the charge q on x 1 must be equals to charge q on x 2, total charge. Total value the charge will be the same. So, that means it will be multiplied by the distance, so it will be say n a n d this will be same this will be same if N D greater than N A. If N D greater than N A that means what?

x 1 must be greater that x 2 if N D greater than N A. Then, x 1 must be greater than x 2. So, that is because of the total uncompensated charge on both the sides of the metallurgical junction will be same. So, we can conclude that the region where it is lightly doped the depletion layer width will be more. So, depletion layer width will be more in this side.

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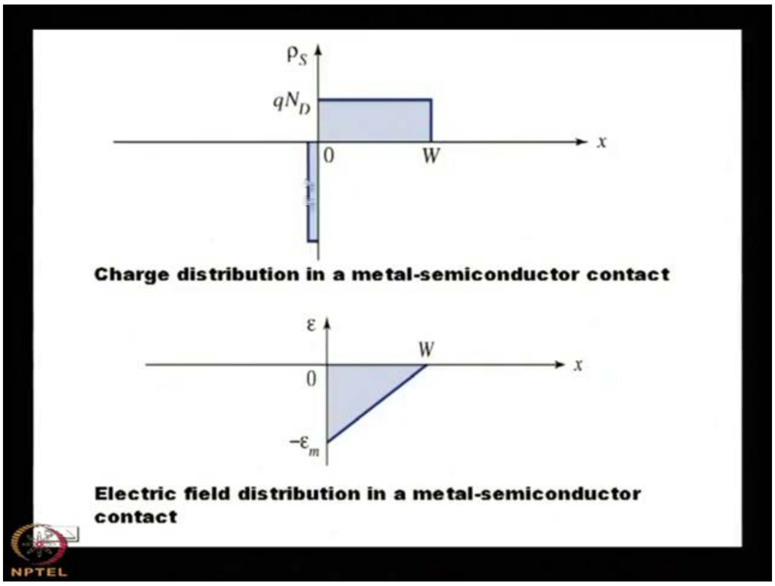

Now, if you consider this thing here, you see that this is the n type semiconductor. This is the metal. The metal is very heavily doped compared to semiconductor n because the number of free electrons in the metal is very, very high compared to the semiconductor not heavily doped. The term doping is not applicable for metal. The exact term should be the number of free electrons on the metal site is more than the number of free electrons on the semiconductor side.

So, the depletion layer will extend on to the semiconductor side, semiconductor side. This rho s is the charge distribution. So, charge will be like this. The electric field will be like this. It is one side in p n junction. You have seen that it will be on the other side also on the p n junction. It will be on the other side also. Here also, it will not be very less on the p n junction. It will have some appreciable area.

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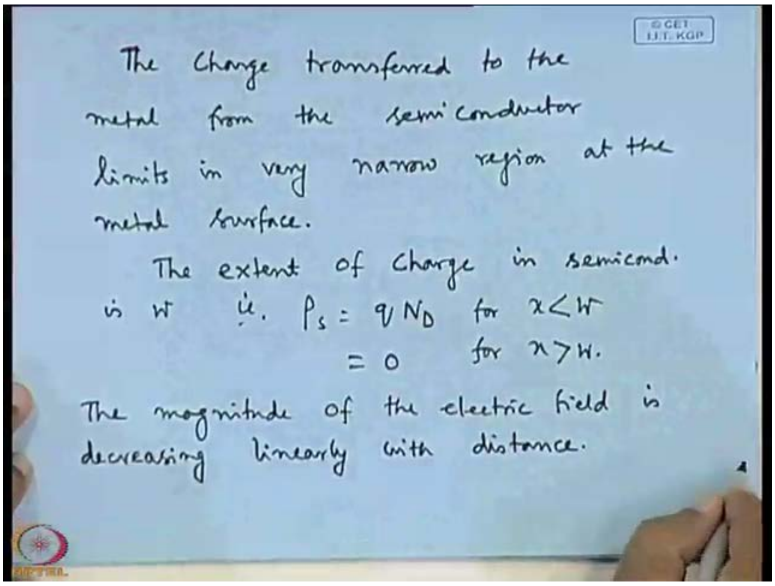

So, the charge transferred to the metal, the charge transferred to the metal from the semiconductor limits in very narrow n region very narrow region at the metal surface. The extent of charge in semiconductor is w that is rho s is equals to q into N D for x less than w and that is equals to 0 for x greater than w. That we have seen in the, we have shown in the graph also the magnitude of the electric field is decreasing linearly with distance.

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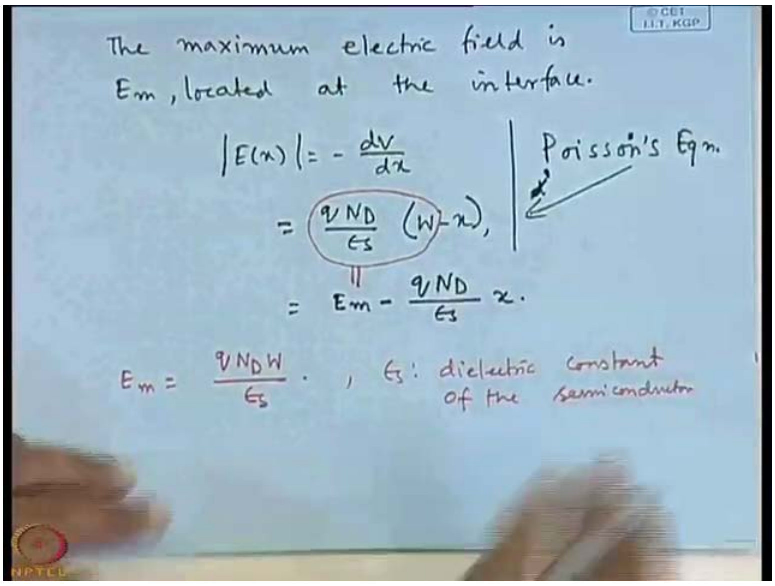

The maximum electric field is E m, located at the interface. Maximum electric field is located on the interface. Now, you know that the electric field is given by minus d V d x. That is equal to q N D by epsilon s w minus x. From does it come? It comes from the Poisson’s equation. That equation is basically related to the electric field and the, or the potential and the charges potential and the charges the relation between the potential and the charges.

So, it comes from the Poisson’s equation. It is this value. This is equals to E m minus q N D by epsilon s into x, where is E m, E m is this thing. That is equals to E m. That means E m equals to q N D w by epsilon s. What is epsilon s? Epsilon is the dielectric permittivity of the semiconductor, semiconducting material. Epsilon s is dielectric constant of the semiconductor.

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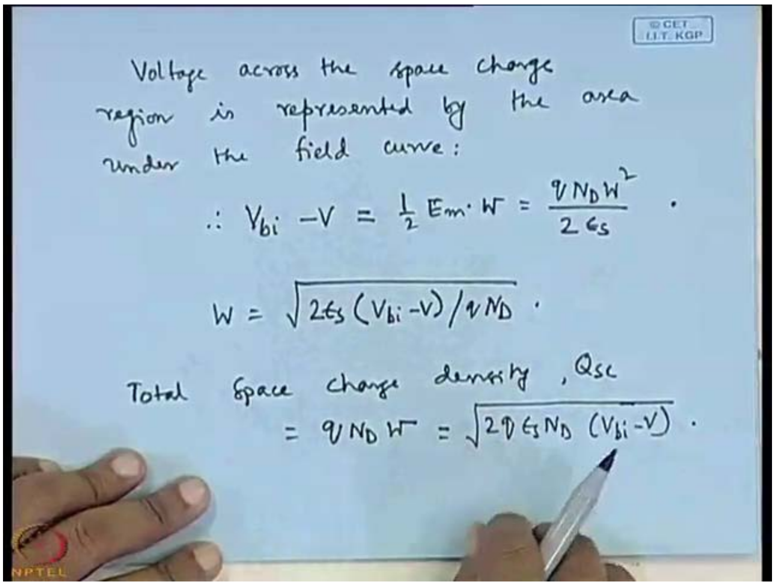

Now, voltage across the space charge by the area under the curve voltage across the space charge region is represented by the area under the field curve. Now, what is the area half base into altitude half base is w altitude is E m. So, that means it is equals to half of E m into w. Now, if you put the value of E m, you will get q N D w square by twice epsilon s. So, that is V b i minus V. That means some forward bias we have applied.

From this expression, we can calculate the value of the depletion layer with w, how very simple. w is given by root over of twice epsilon s V b i minus V by q into N D. So, this is the width of the depletion region. This is the value of the depletion region. Now, what is the space charge density? In the semiconductor, space charge density that means total charge in the depletion layer. What is that? How it can be calculated? It can be calculated by you see total space charge, total space charge density, it is Q s c.

It is given by equals to q N D into w. N D is the number of donors. w is the depletion layer width and q is the charge. So, total charge is q into N D into w. Now, you put the value of w here from this expression to here.

So, what you will get?

Student: 2 q by epsilon s N D.

2 q.

Student: Epsilon s into N D.

Yes.

Student: V b i minus V.

V b i minus V.

So, this is the total space charge. Remember that for forward bias this V will be plus. For reverse bias, it will be? Plus. Minus V r. Yes, that means plus V r. Sure. Now, from this space charge, you can calculate the capacitance, charge divided by voltage is the capacitance.

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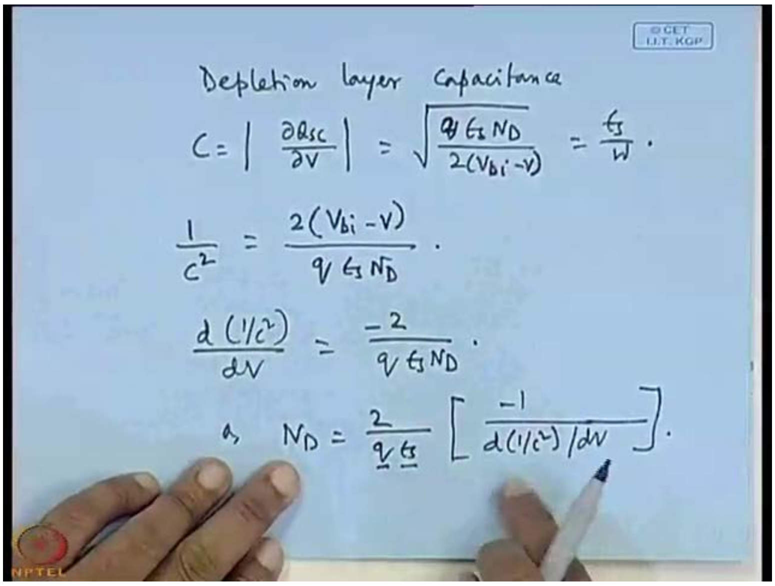

So, the capacitance depletion layer capacitance, that is c equals d Q, d Q s c by d V that is equals to root over of Q epsilon s N D by 2 V b i minus V that is equal to epsilon s by w. So, this is the total capacitance in the depletion region. What is 1 by c square? That is the 1 by c square. Now, if we differentiate 1 by c square with respect to v, if you differentiate 1 by c square with respect to V, then what you will get? d 1 by c square by d V that is equals to?

Student: Minus sir, sir, minus sign will be there.

N D is equals to 2 by q s minus 1 by d of 1 by c square by d V. So, that means N D can be calculated from this expression. You see that q is the electronic charge and epsilon s is the dielectric constant of the material. So, those are constants available from the literature that means if you can plot 1 by c square versus V, if you can plot 1 by c square versus V, then from the slope of that curve, you can calculate the value of the N D. If N D is constant throughout the material, which will be there if that doping is uniform, and then N D will be constant throughout the material. Then, it will be a straight line. Then, it will be a straight line.

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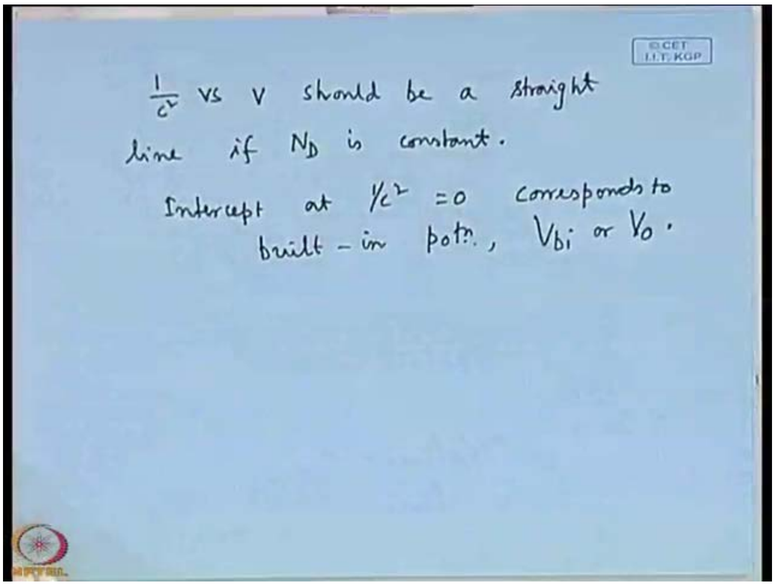

So, I can write down 1 by c square versus V should be a straight line if N D is constant. Intercept at 1 by c square equals to 0 corresponds to what built in potential that is V b i or V 0, the same thing. So, from the, from that curve that means 1 by c square versus V. 2 important things we can obtain; one is the value of N D that is from the slope of the curve and another from the intercept of the curve, V b i. V b i why? This is because you see from this expression when V equals to 0 equal to that means when V b i minus V equals to 0 V will be V b i. So, from the intercept, you see that intercept at 1 by c square equals to 0 corresponds to built in potential V b i. Once you know V b i, you can calculate phi B n. Once you know V b i, you can calculate phi B n. So, that is also very important relation and you see that in this plot.

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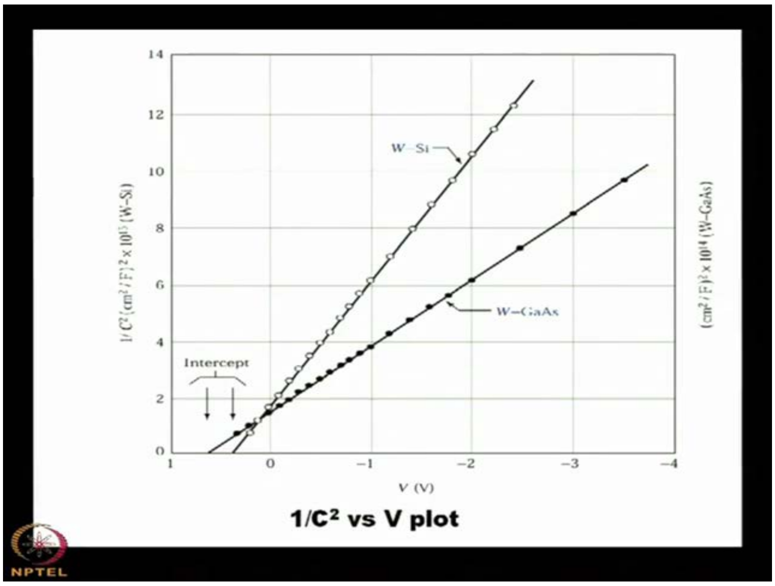

I have shown 1 by c square versus V. This is the intercept that means 1 by c square equals to 0. This is the intercept. This is the intercept. So, from the intercept, you can calculate V b i. From the slope, you can calculate N D. So, 1 by c square versus V plot is very, very important for semiconductor. iI is applicable for p n junction. Also, if you want to calculate the barrier potential in p n junction, you use 1 by c square versus V plot. If you want to know the doping concentration, then also you can plot 1 by c square versus V because that slope will give you the concentration of the carriers. So, it is 1 by because you had in your mind that 1 by c square. Why you are why we are making so much mathematics?

It is because of this plot because straight forward you can have from this graph. It is straight forward because you see that you have to measure current or voltage or capacitance as a current or capacitance as a function of voltage. You have to plot it from the plot. You can straight forward. You can take the value and put to determine a particular parameter. Now, with this idea, let us solve this problem.

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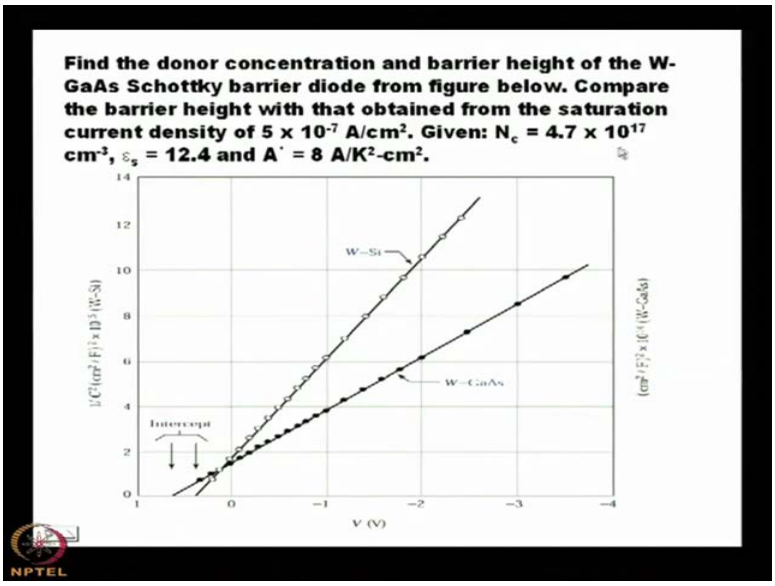

This one, find the donor concentration and barrier height of the tungsten gallium arsenide Schottky barrier diode from figure below. Compare the barrier height with that obtained from the saturation current density of this. Given this N c equals to 4.7 into 10 to the power 17 per centimetre cube. Epsilon s equals to 12.4 and effective Richardson constant A star equals to 8 ampere per Kelvin square centimetre square.

That means from this problem, you can calculate the barrier height from the c V because it is given that from the figure below. This figure is related to 1 by c square by V 1 by c square versus V. Now, you you try this problem. Find the donor concentration and barrier height from J s. It is very easy from J s saturation current density is given. A star is given. So, first part is very easy. In this case, the second part you see that J s is equals to A star T square e to the power minus q phi B n by K T or phi B n is equals to K T by q l n A star T square by J s.

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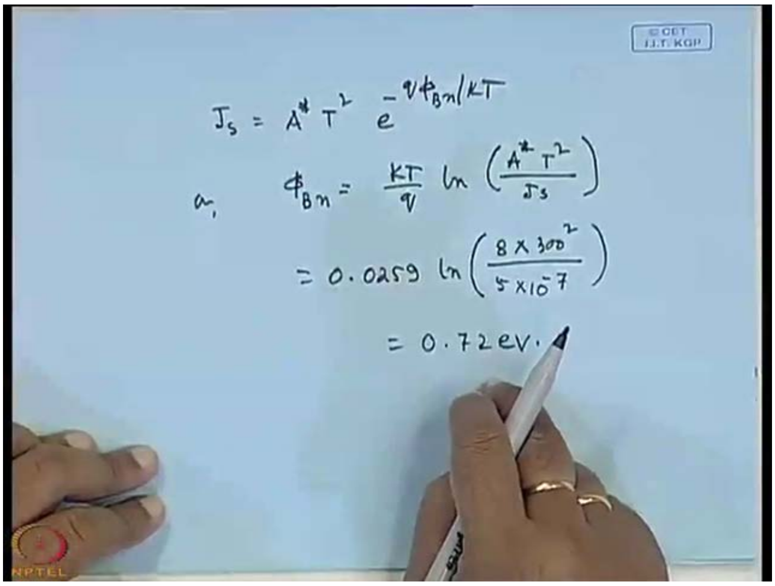

In this case, the second part you see that J s is equals to A star T square e to the power minus q phi B n by K T or phi B n is equals to K T by q l n A star T square by J s, J s that is equals to 0.0259 l n, A star is 8 into 300 square by J s is given 5 into 10 to the power minus 7. You see it is given. So, it will be 0.72 electron volts. So, the barrier height is 0.72 electron volts. It is from the I V measurement. Remember that it is from the I V measurement. Clear any doubt. Now, from c V measurement, what is the value the curve is given? The curve is given.

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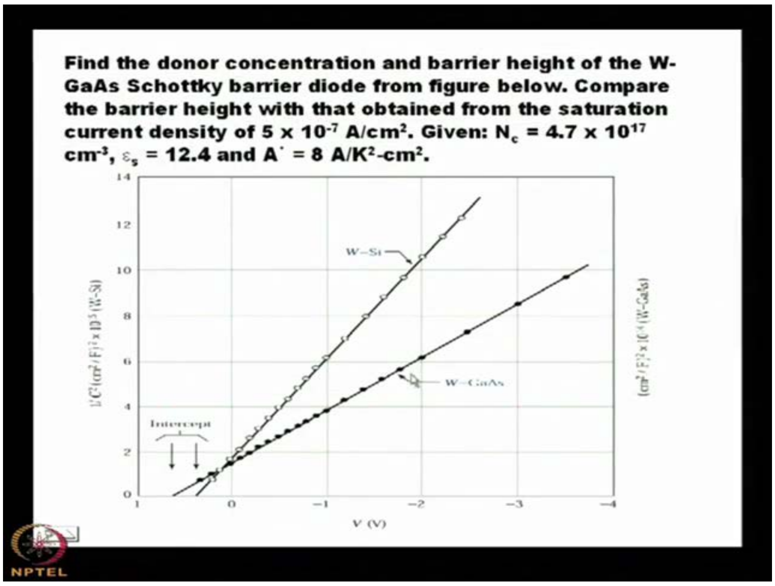

So, once the curve is given, you see for gallium arsenide, you have to calculate 1 by d of 1 by c square versus d V 1. That means you have to calculate d 1 by c square d V. So, if you consider this gallium arsenide curve, what is the value at minus 2? The value is?

Student: 1 or 2.

What is value at 0?

Student: It is 1.8. 1.6.

You can take minus 1. What is the value?

Student: Almost 3.9.

3.9.

So, you take the difference 4.2 into 10 to the power 14. Here, you see it is, 10 to the power 14, not this scale. This scale is for silicon. It is given, it is left scale is for silicon. Right scale is for gallium arsenide. So, it is say 6.2 into 10 to the power 14 minus 3.9 into 10 to the power 14 by minus 1.

Minus 1, why?

Because, minus 2 minus minus is 1; so, it is minus 1. So, thereby you can calculate you see, this value you can calculate. This value you can calculate. So, if you know this value, then N D can be easily available.

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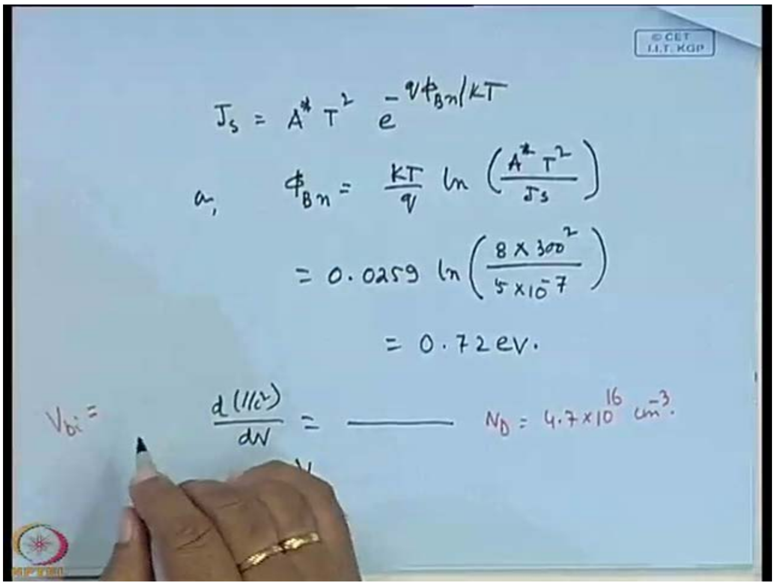

N D for this case, N D for this case, you can write down 4.7 into 10 to the power 16 centimetre cube inverse. You can try on your own, 4.7 into 10 to the power 16. N D is given. Now, what is V N? What is V N? What is V b i?

Student: Sir, V b i is K T by q l n N A into N D by A square.

V b i is?

Student: K T by q l n N A into N D by A square.

No, no, but from here, you can calculate the intercept.

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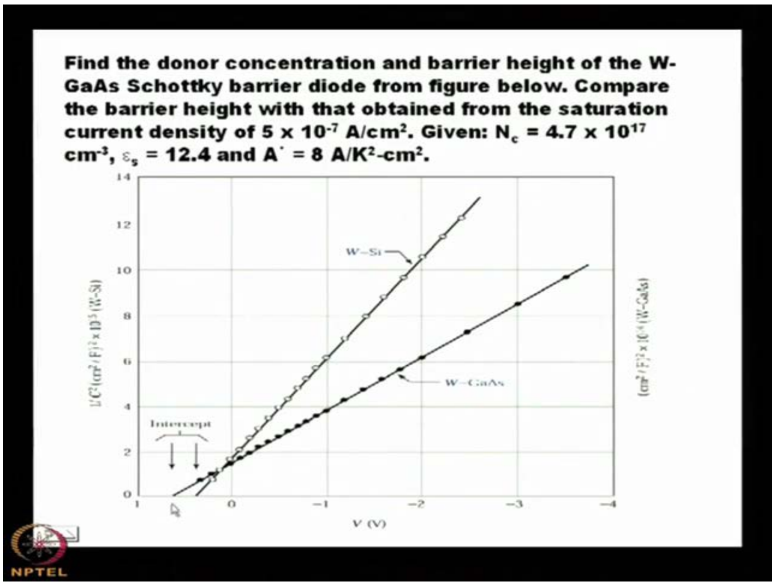

How? Graph is given. So, the intercept you can calculate. What is the value for gallium arsenide? It is say how much?

Student: 1.6.

Minus 1.6.

Student: 0.4.

0.4 or 0.5 whatever be the case, say 0.4 volt.

Student: It should be 1.1.

No no no no no. 0.4 is the value.

Now, it is not 0.4. It is, say you have to measure from 0.

Student: 0.6.

0.6.

0.6 or 0.7. Say, it is 0.7 volt because you have to measure from 0 say, it is 0.7 volt. So, you know N D. You know V b i. So, how to calculate phi B? Phi B n will be V n plus V b i phi B n equals V b i plus V n V b i is 0.7 volt and V n. You have to calculate what is V n? V n is the distance between the Fermi level and the conduction band. So, this V n is nothing but K T by q l n N c by N D. This expression we have earlier deduced because these are very useful expressions and always you have to make use of it. So, it is K T by q l n N c by N D.

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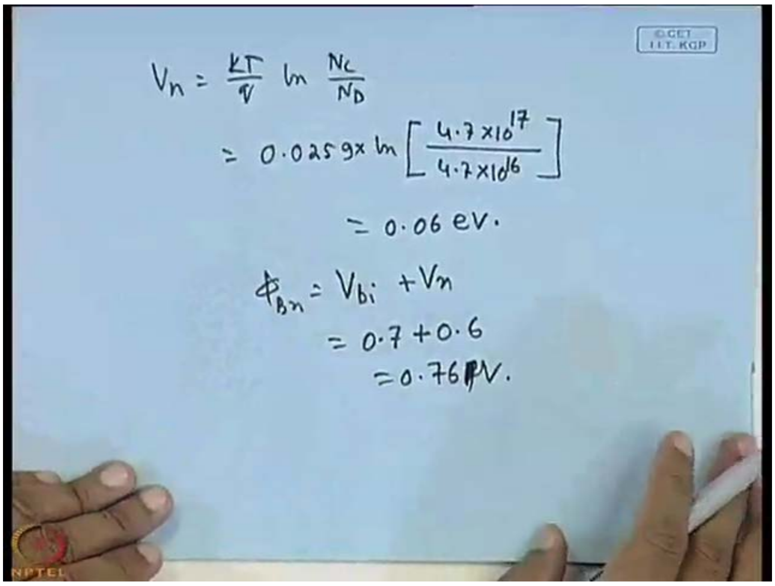

So, if I calculate the values, you will find that V n is equals to K T by q l n N c by N D or K T by q is 0.0259 multiplied by l n, N c is how much? It is 4.7 into 10 to the power 17. 4.7 into 10 to the power 17 and 4.7 into 10 to the power 16 N D. This is equal to 0.06 electron volts. So, phi B n is equals to V b i plus V n. V b i is 0.7 from the intercept of the 1 by c square on V axis. The intercept of 1 by c square at V equals to 0.7 plus 0.6 that is 0.76 electron volts. What was the value from I V measurements?

Student: 0.72.

0.72. Here, it is 0.76. So, almost you find that there is an increase of 5 percent. That is volt. That is volt, not electron volt. It is volt. This is also volt. This is also volt. If you multiply that volt with q, it will be electron volt. It is very simple. The same value will be there that means see here it is phi B n equals to 0.72 volt. If you multiply by q, it will be 0.72 electron volts. It is very simple. So, you see that 2 different values we encountered. One is the phi B n from I V measurement, which is 0.72. Another is phi B n from c V measurement, which is 0.76. So, that means barrier height from capacitance is 4 percent larger than the barrier height from the I V measurements. The reason is that there will be interface states. For that reason, it will be different. It will be different. So, this is the example. You take one homework.

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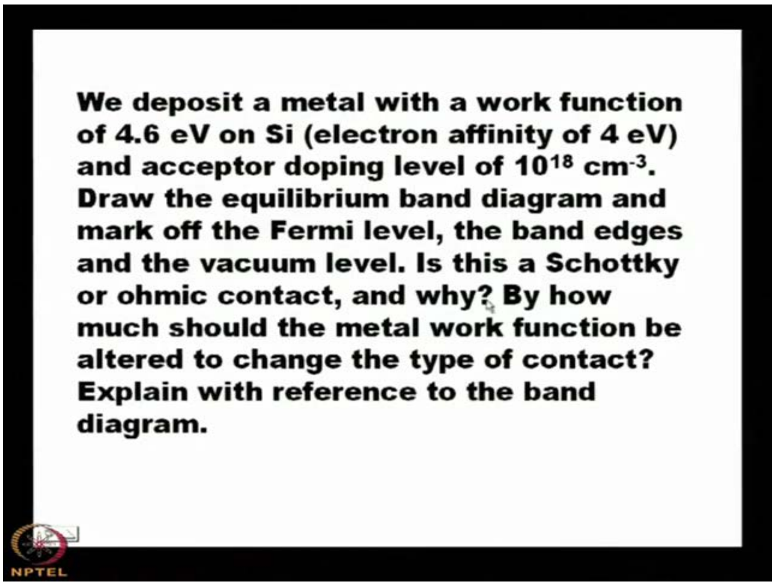

So, the earlier one and this one you have to submit by the next week or by Friday, this week. Today is Tuesday. Yes, by Friday. You submit it in a piece of paper. You write your name roll number. We deposit a metal with a work function of 4.6 electron volts on silicon. The electron affinity is given as 4 electron volts.

The acceptor doping level is 10 to the power 18 centimetre cube inverse. Draw the equilibrium band diagram and mark off the Fermi level, the band edges and the vacuum level is this, a Schottky or ohmic contact. Why by how much should the metal work function be altered to change the type of contact? Explain with reference to the band diagram. So, before this, you will get a copy before this. Just let me introduce you the ohmic contact because in this problem, ohmic contact is required, concept of ohmic contact is required.

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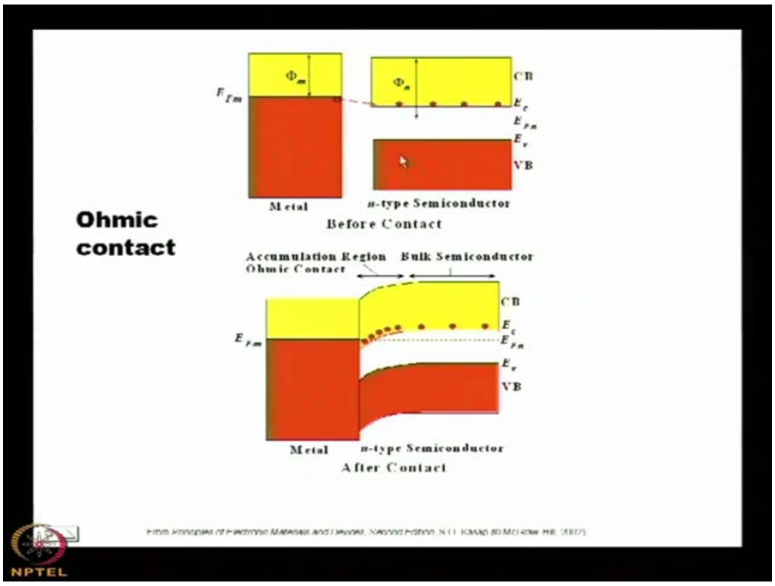

See here; the metal work function is less than the semiconductor work function. It is n type semiconductor. The metal work function is less than the semiconductor work function. Then, if you join, what will happen? Electrons are coming from metal (( )).

Yes, electrons will come from metal and it will be accumulated on the semiconductor interface, semiconductor surface or interface. So, it will be accumulated. So, at the semiconductor surface, there will be more number of electrons compared to the bulk. In the Schottky case, what happened? More number of electrons was in the bulk compared to the depletion layer because there was a depletion layer at the interface.

Here, there is no depletion layer rather there will be accumulation layer. See because of this accumulation layer, the band bends upward. For depletion layer, the band bends downwards, downward. Here, it bends upward. The mechanism is as same E C minus E F.

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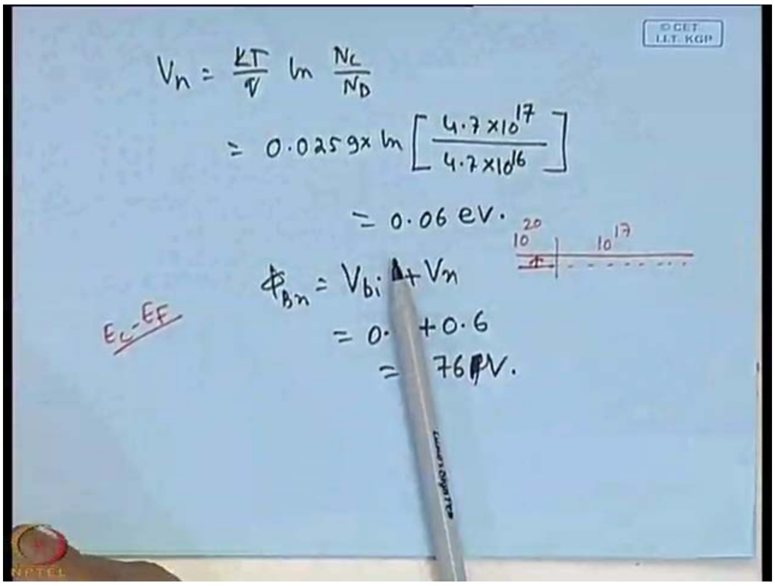

The value of E c minus E f, if you have to determine, here at the interface, E c minus E f is very less. Why? This is because there is more number of electrons. Accumulation of electrons was there. So, if you consider this type of a diagram, suppose up to this point, it is 10 to the power 17. But, if it is 10 to the power 20, then what will happen? This level will move very close to the conduction band.

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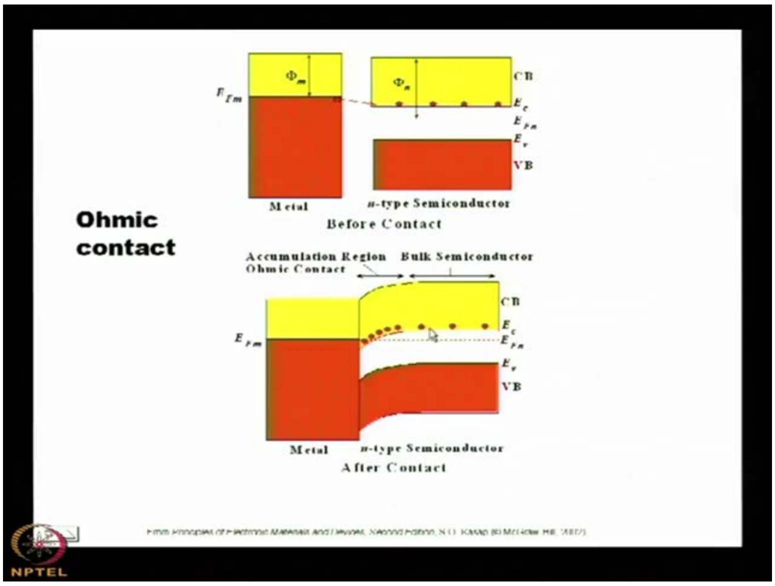

This is because the value of E c minus E f will be less. If the value is sufficiently high, then it can even go upwards. Here, you see that the band bending was such that it even crosses the Fermi level near that junction because of the heavy accumulation of the electrons. So, that means whatever be the polarity, always there will be flow of electron from the metal to the semiconductor; from the semiconductor to the metal, always there will be flow of electrons, not like your Schottky case.

In Schottky case, there was a barrier. Here, there was no barrier. If you contact it with positive or negative, whatever be the polarity, the electrons will always flow from this direction to that direction or from that direction to this direction. So, that is known as the ohmic contact. Here, the contact resistance will be determined not by the interface because there is sufficient number of electrons accumulated. So, the resistance is very, very less. It will be limited by the resistance of the bulk material. The current will be limited by the resistance of the bulk material.

So, in ohmic contact, the flow of electron is in both the sides. So, thereby the current will be same. You use positive bias or negative reverse bias. It will be the same current that will flow from one end to the other. It will be limited by the resistance of the bulk material (( )). So, that is the ohmic contact.

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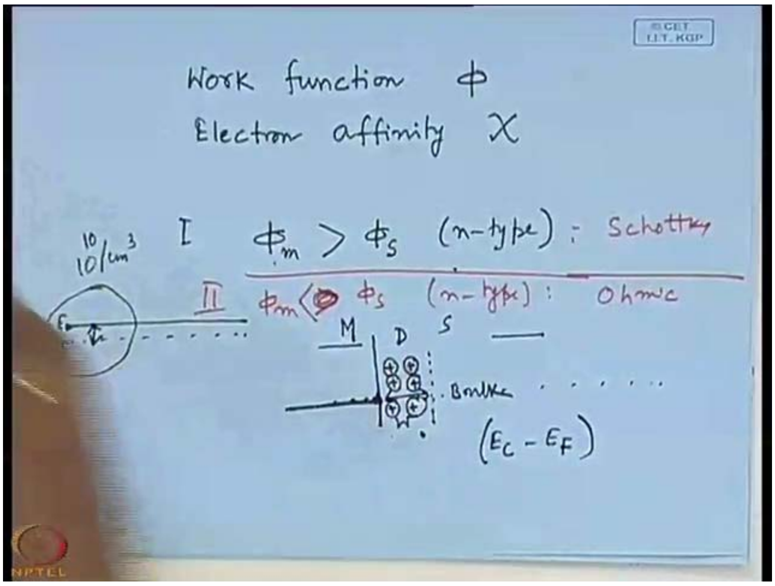

So, that means if we start from this thing that; here, you see that we have started with this slide that phi m greater that phi s for n type, we see that it is Schottky; and number 2 case is that phi m greater than phi s for n type and it becomes ohmic. So, you expect that when phi m is less than phi s for p type, it will be Schottky. When phi m is less than phi s for p type, it will be ohmic. The reverse thing will happen In case. Where? From ohmic.

Student: Sir, second line.

Sorry, sorry, phi m less than phi s. Yes, it is. You see that it is phi m less than phi s. So, it is n type. It is ohmic. So now, you are in a position to say when there will be ohmic contact, when there will be your Schottky contact will depend on the metal work function and the semiconductor work function.

Thank you.