Fundamentals of electronic materials, devices and fabrication

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Assignment - 4
Metal - semiconductors junctions

In today's assignment, we are going to look at Metal-semiconductor junctions.

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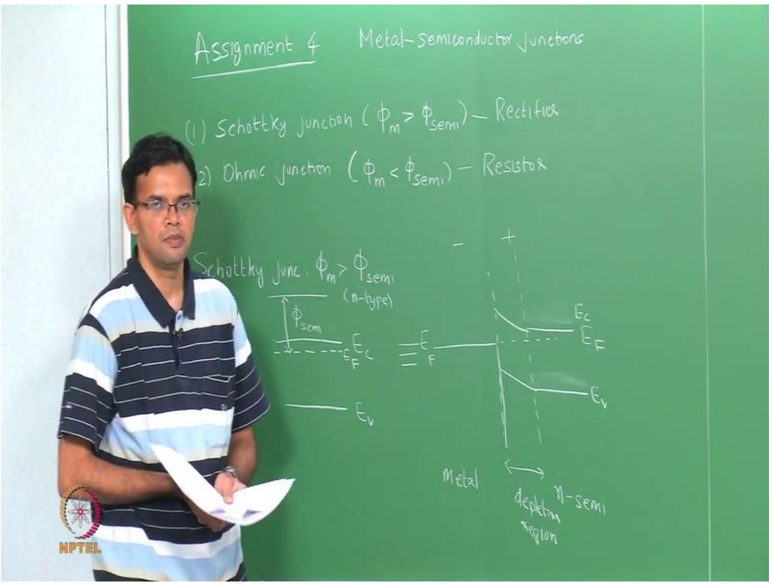

This is assignment 4. So, in class we looked at 2 kinds of Metal-semiconductor junctions, one was the Schottky junction or the Schottky contact and the others was the Ohmic junction or an Ohmic contact. So, We saw that a Schottky junction forms when the work function of the metal, so phi m is greater than the work function of the semiconductor. In the case of an Ohmic junction it is the reverse, the work function of the metal is less than the work function of the semiconductor.

We also saw there are Schottky junction essentially behaves like a rectifier, so it conducts the current in the forward bias and does not have any conduction in the reverse bias. So in this way a Schottky junction is similar to a p-n junction, which is also a rectifier. And Ohmic junction on the other hand from the name is just a pure resistor, it conducts both in the forward and the reverse bias and the conductivity is defined by the conductivity or the resistivity of the semiconductor material. So, In today's assignment, we will be looking mostly at Schottky junctions, we will do some calculations on the Schottky barrier, the contact potential and also the current in the forward and reverse bias.

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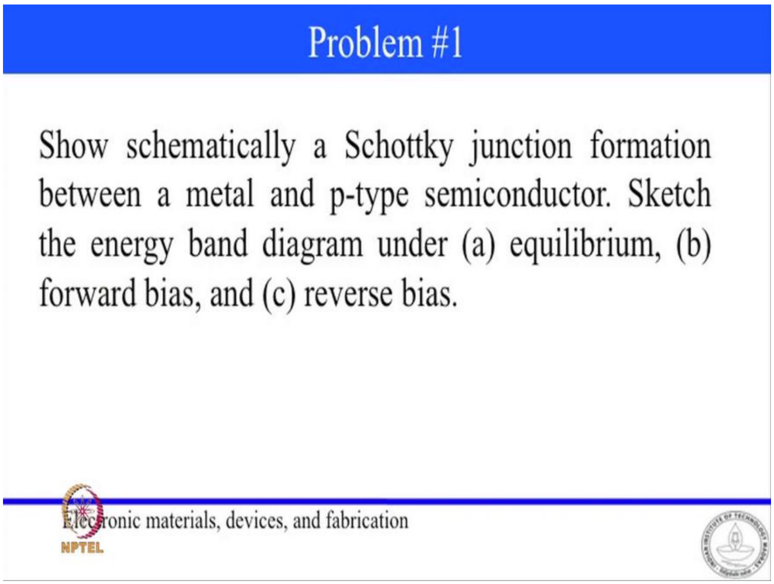

So, let us go to problem number 1. So, We want to show how a Schottky junction is formed between a metal and a p-type semiconductor. So, we can do this by sketching the band diagram under equilibrium, forward and reverse bias. So, in class when we looked at the example of a Schottky junction, we look at a metal and then n-type semiconductor. Let me draw that first under equilibrium, and then from there we will look at a metal and a p-type semiconductor. So, We said a Schottky junction is formed when phi m is more than phi semi, so we will start with the metal here, we just draw the slightly up. This represents the vacuum level, this is the Fermi level of the metal and this space is a work function of the metal. So, all the energy levels below this are completely full. So, we will start up with an n-type material. So, This is your n-type material; you have E_c and E_V. So, E_V is a valence band and E_c is the conduction band. It is an n-type, so the Fermi level is closed to the conduction band. Once again here the distance between the Fermi level and vacuum level is a work function of the semiconductor.

So, When these 2 are brought together in contact, we know that in equilibrium the Fermi levels must line up. So, we have excess electrons that are there in the conduction band of the semiconductor, these will go and occupy all the empty states in the metal. So, there is a net positive charge on the semiconductor side and net negative charge on the metal side. The electric field goes from positive to negative, and the bands bend up in the direction of the field. So, if you were to draw this under equilibrium, so I will just mark my junctions this is E_F, so this is my metal side and this is the n type semiconductor. This is the E_F of the semiconductor. So far away from the junction the semiconductor will still be n-type, let me draw the bands slightly closer. This is n type E_c and E_V, there is a net positive charge on the semiconductor and net negative charge on the metal and the bands will bend up. So, This in turn forms the depletion region and this is the band diagram at equilibrium. So, this is a case of a metal and in n-type. This is similar to what we saw in class. So, let us now draw one for a metal and a p-type.

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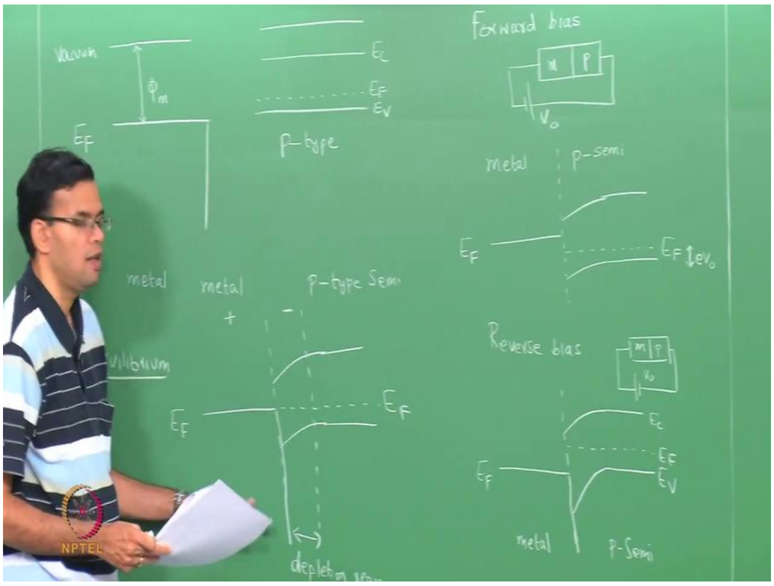

So, Once again we have the vacuum level, you have the Fermi level of the metal and this is phi m and this is the metal. We now have a p-type semiconductor. So, This is E_c, this is E_F and this is E_V. So, it is a p-type semiconductor so that the Fermi level is close to the valence band.

So, we can use a same argument that we used for a metal and then n-type. Now, that the argument is reversed, so once again when the junction forms the Fermi levels must line up. But, instead of excess electrons going from the semiconductor to metal, we now have the electrons moving from the metal to the semiconductor or the holes moving from the semiconductor to the metal so that there is a net positive charge on the metal side and net negative charge on the semiconductor sides. And bands will bend down as we go from a semiconductor to the metal. So, This, if we draw in equilibrium, the Fermi levels must line up so I will put an interface. So, E_F and E_F, metal and p-type semiconductor far away from the junction, your material is still p-type, and then the bands bend down so that there is a net negative charge and a net positive charge and this is the depletion region.

So, the band bending here is similar to that of a metal in an n-type, but it goes the other way. We now want to draw the energy band diagram in forward and reverse bias. So, in the case of a forward bias, so this is my metal, this is my p-type. The metal is connected to a negative charge and the p-type is connected to a positive charge. So, In this case, the Fermi level shift and the barrier essentially is lowered. So, we can once again draw this; that is my interface that is my metal. Now, the Fermi levels no longer align and for the p-type the Fermi level is shifted down and this shifting down is given by your external potential that is V_o.

So here, the barrier for the motion of the electron and holes is reduced so that there is an increasing current, when you apply an increasing voltage. In the case of a reverse bias, So, m and p; the metal is connected to positive, the semiconductor is connected to negative. Once again, the Fermi levels do not line up, but instead of shifting down the Fermi level is now shifted up. So, that is my interface E_V, E_c and E_F; this is the metal, this is the p-type semiconductor. So, this is a situation where we have a metal and a p-type in equilibrium is the energy band diagram forward bias and reverse bias.

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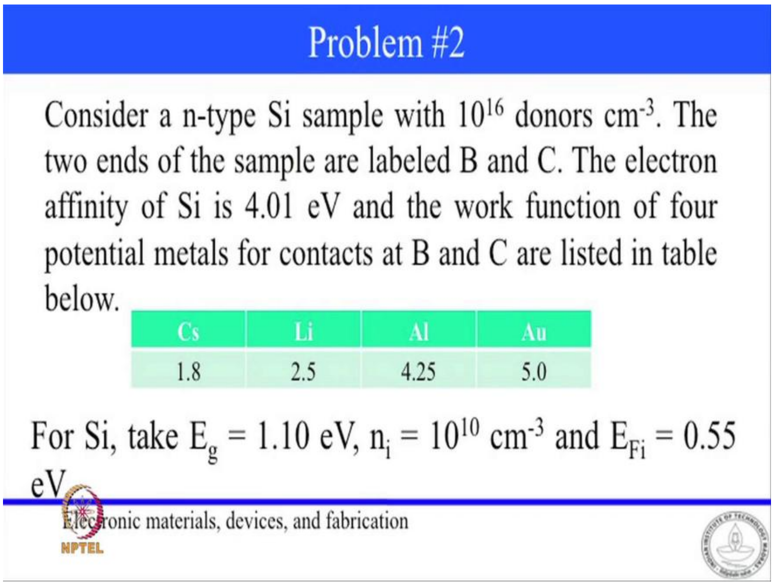

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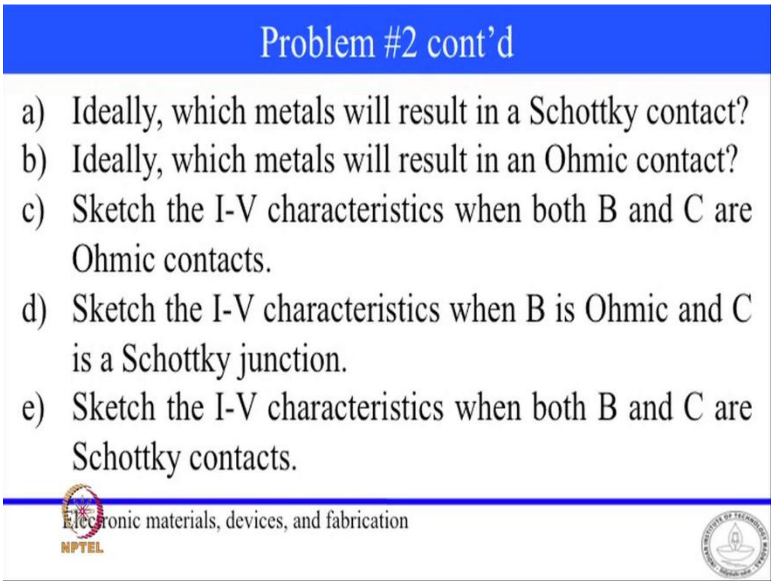

Let us now go to problem number 2.

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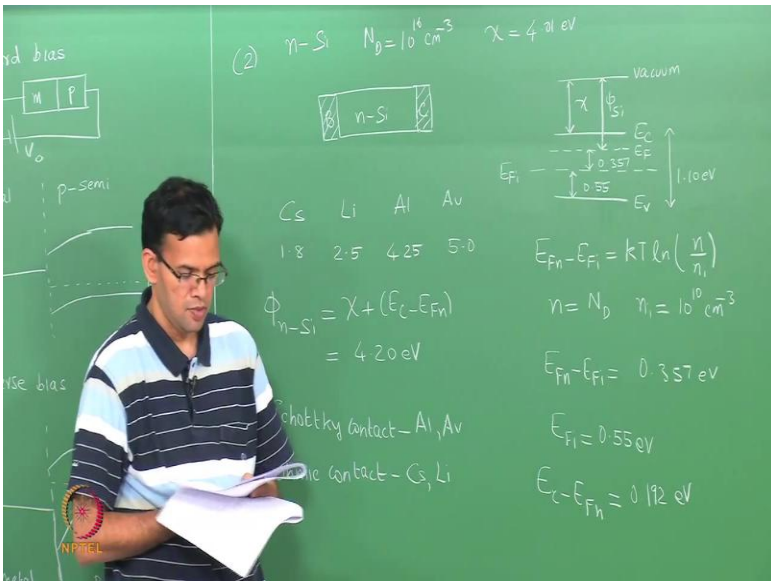

In problem 2: We have an n-type silicon with 10^{16} donors cm^{-3}. Now, n silicon with N D is 10^{16} cm^{-3}. The 2 ends of the sample are label B and C. So, we have 2 ends, there are essentially 2 metals at the either end so, if we were to draw a schematic, this is my n silicon and I have B and C on both sides. Let me just shade them to show you that they are essentially metal contacts. The electron affinity of silicon is given, so χ is 4.01 eV and there are 4 potential metals which can be used for these contacts and their work functions are given. We have cesium, lithium, aluminum and gold, and the work functions are essentially given.

So, the first thing we need to do is to calculate the work function for the semiconductor. So, We can draw an energy band diagram; this is vacuum we have only drawing the semiconductor side E_c and E_V. It is an n-type semiconductor, so the Fermi level will be closer to the conduction band. Now, the electron affinity is the energy difference between the conduction level and the vacuum level. This is essentially chi; we need the work function so we need phi of the silicon. To know that we need to know the position of the Fermi level and that can be calculated from the concentration of donors in the materials. So, we can just say E_{Fn} - E_{Fi} is $kT \ln \frac{n}{n_i}$. So, n is nothing but N_D, it is fully ionized. n_i for silicon is given and you also saw this during the previous assignment, it is nothing but 10^{10}. From this we can calculate the value of E_{Fi} - E_{Fn}. We can also know the position of the intrinsic Fermi level, so we can calculate from the values of N_c or N_v. In this particular case, E_{Fi} is given to be 0.55 electron volts and the band gap of silicon is

1.1. This whole thing is 1.1 eV, E_{Fi} is given to be the center of the band gap and this is 0.55, this distance is also known and the value for this is 0.192, 0.357 sorry, this is 0.357.

So, everything else is known except for this, so E_c - E_{Fn} is nothing but 0.192. So, from this we can calculate the work function of the silicon. So, φ_{Si}, since it is n-type I will just write phi of n is nothing but $\chi + (E_c - E_{Fn})$ which works out to be 4.20 eV. If you look at the various parts of the question, part-a ask, which metals will result in a Schottky contact? We have a Schottky contact when the work function of the metal is greater than the work function of the semiconductor, so those who essentially aluminum and gold. So, Schottky contact would be aluminum and gold, which metal will result in an Ohmic contact so in Ohmic contact is 1, where it is reverse. The work function of the semiconductor is higher. So ,it is just cesium and lithium.

So part-c, sketch the I-V characteristics when both B and C are Ohmic contacts. Let me draw that, so B and C are both Ohmic contacts. In Ohmic contact is nothing but a resistor, so when you have both B and C to be Ohmic then the whole thing just acts as a resistor.

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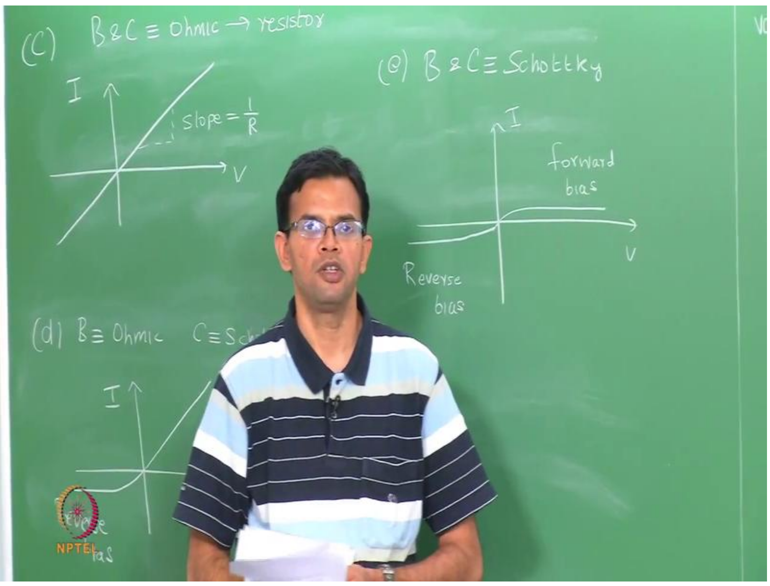

So, the I-V characteristics will just be a straight line and the slope of this line will be just 1 over R. Part-d, sketch the I-V characteristics when B is Ohmic. So, B is Ohmic and then C is Schottky.

We have one Ohmic, and one Schottky junction. So, in the case of a forward bias, you will have a Schottky junction will be essentially a high conductor, so it will start to conduct. In this particular case, the resistance will be determined by the highest resistance point which is your Ohmic contact. Here, in the case of forward bias, so if we were to draw I versus V, you have a highly conducting junction which is junction C and you have a resistor which is junction B; So, this will essentially behave like a resistor. In the case of a reverse bias, C is essentially reverse biased so that there is very low conductivity through that. That will essentially determine the conductivity of the entire circuit so that you have a very low conductivity in reverse bias. For the same is true, when B is Schottky and C is Ohmic the curve will be similar.

In part-e, sketch the I-V characteristics when both B and C are Schottky. So, in this particular case, if one of the junctions is forward biased the other junction will be reverse biased and so on. So, whether you are in the forward or the reverse there always be 1 junction that is reverse biased which will have very low conductivity. So, the I-V characteristics in this particular case will be a very low current in both forward and reverse bias. So, This kind of a situation is very important when you are trying to make electrical contacts to a semiconductor. Usually we have to make 2 contacts ideally, we want this contacts to be Ohmic because we do not want the contact itself playing a role in determining the I-V characteristics, but there could be diodes based on the Schottky affect. These are Schottky diodes. In this particular case, we would want 1 junction to be essentially a Schottky junction and the other to be an Ohmic junction.

So, let us now go to problem 3.

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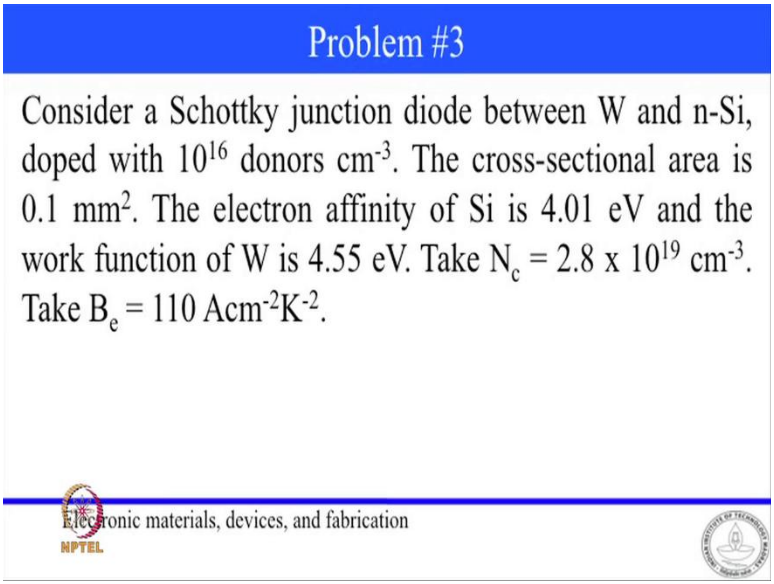

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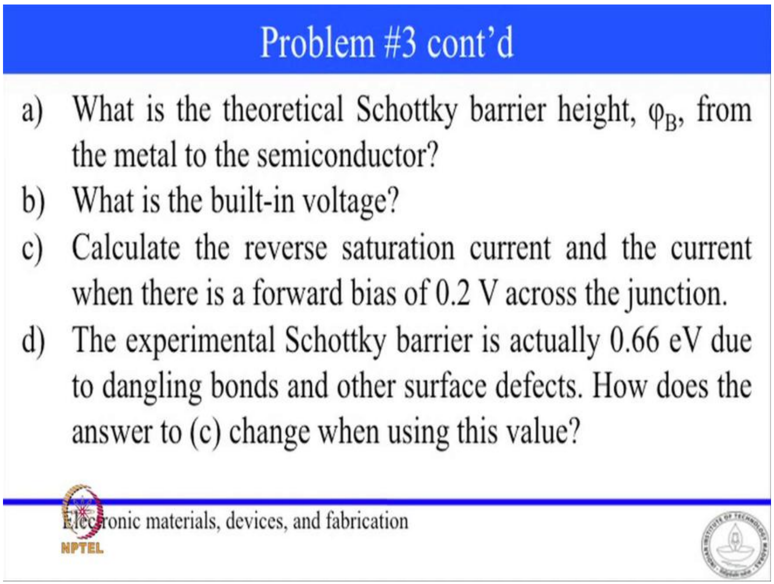

So, problem 3: you have a Schottky junction diode between tungsten and n-type silicon. The silicon is doped with 10^{16} donors cm^{-3}.

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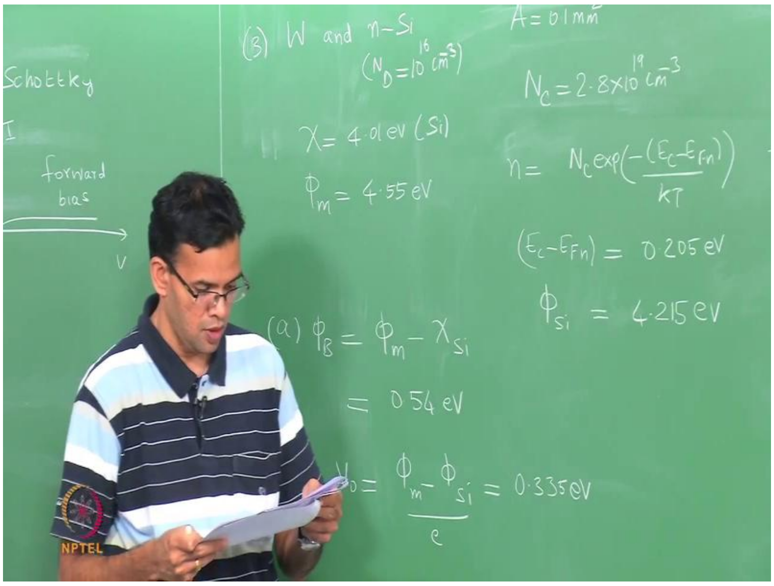

The cross-sectional area is given, so A is 0.1 mm^2, the electron affinity of silicon is given same as the last problem 4.01 eV and the work function of the metal is given to be 4.55 electron volts. So, once again we need to calculate the work function of the semiconductor. We can do the same thing that we did in the last problem. In this particular case, the effective density of states the conduction band is given, so that is 2.8×10^{19}.

We would use this directly to calculate the position of the Fermi level. So, n is nothing but $N_c exp\left[\frac{(-E_c - E_{Fn})}{kT}\right]$, from which you could calculate $E_c - E_{Fn}$. So, n is nothing but N_D which is your concentration of donors. N_c is given everything else is known, so $E_c - E_{Fn}$ is essentially 0.205 electron volts. So, from this we calculate the work function of silicon to be 4.215 electron volts. We can draw this in a band diagram, so I will just draw it schematically. This is my tungsten, work function of tungsten is given so 4.55 and this is my n-type semiconductor, so E_c, E_V this is 4.01, this whole thing is 4.215 and this is 4.55.

Again, we have a case of a Schottky junction between tungsten and n-type silicon. So part-a, we want to calculate the theoretical Schottky barrier. So, you want to calculate φ_B; φ_B is the Schottky barrier and that is essentially the work function of the metal minus the electron affinity of the silicon. The Schottky barrier represents the barrier for the electron to move from the metal to the semiconductor side. So, you have an electron going from E_F to the conduction band, so this is just $\varphi_m - \chi_{Si}$. You can put in the numbers and this is 0.45 electron volts. Then we want to calculate the built-in voltage. So, V_o is nothing but $\frac{\chi_m - \varphi_{Si}}{E}$. So, E is just to convert it from electron volts to volts, it is a difference between the work functions. This we can substitute and the answer is 0.335 electron volts.

In part-c, we need to calculate the reverse saturation current and also the current when there is a forward bias of 0.2 volts across the junction.

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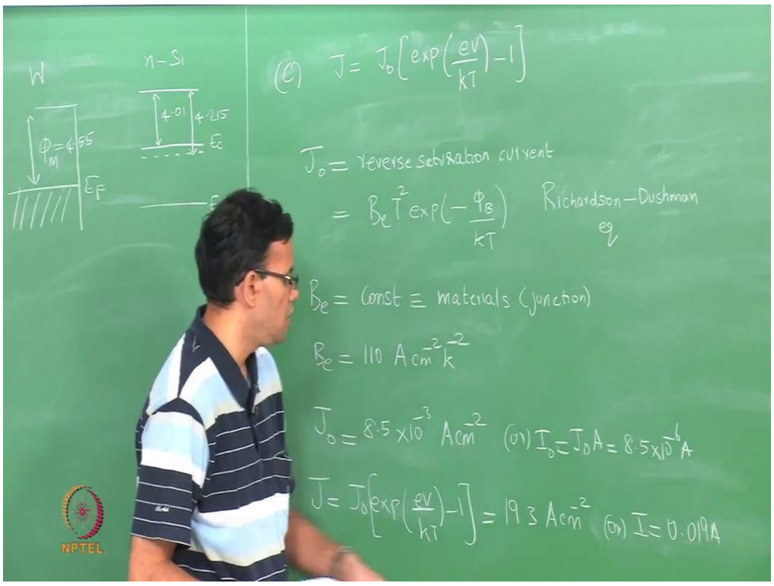

So part-c, we want to calculate the current in the junction. So, In the case of a Schottky diode, it is possible to write an expression for the current, this is something we do not see during the course of the lecture. We can write the current J as some constant $J_o \left[exp\left(\frac{eV}{kT}\right) - 1\right]$. So, V here is your external potential, J_o is your reserve saturation current and $J_o = B_e T^2 \left[exp\left(\frac{-\phi_B}{kT}\right)\right]$. So, this is called a Richardson-Dushman equation and it is actually used to calculate the current during thermionic emission from a metal. So, B_e is usually a material constant, it is a property of the interface. Whether you have tungsten and silicon or platinum and silicon, platinum and germanium the value of B_e will change. So, B_e is a constant that depends upon the materials which is basically is a property of the junction.

So, In this particular case, the value of B_e is given, so B_e is 110 A cm^{-2} K^{-2}. So the value of ϕ_B, we calculated earlier this is nothing but a Schottky barrier. From this problem you can calculate J_o. Everything else is known, temperature is 300. So, from here J_o is essentially 8.5 x 10^{-3} A cm^{-2}. If you want to calculate the current, you multiply this with the area, so current I is J_o x A which is 8.5 x 10^{-6} A or 8.5 μA.

We can now calculate the current during the forward bias. So, J is $J_o\left[exp\left(\frac{eV}{kT}\right)-1\right]$, so usually the exponential term dominates. The external voltage is given to be 0.2 volts. So, we can substitute the numbers and J comes out to be 19.3 A cm^{-2} or the current I is just 0.019 amperes. So, this is the current during forward bias, you can see that it is nearly 4 orders of magnitude higher than the current during reversed bias, this is why a Schottky junction essentially a very good rectifier.

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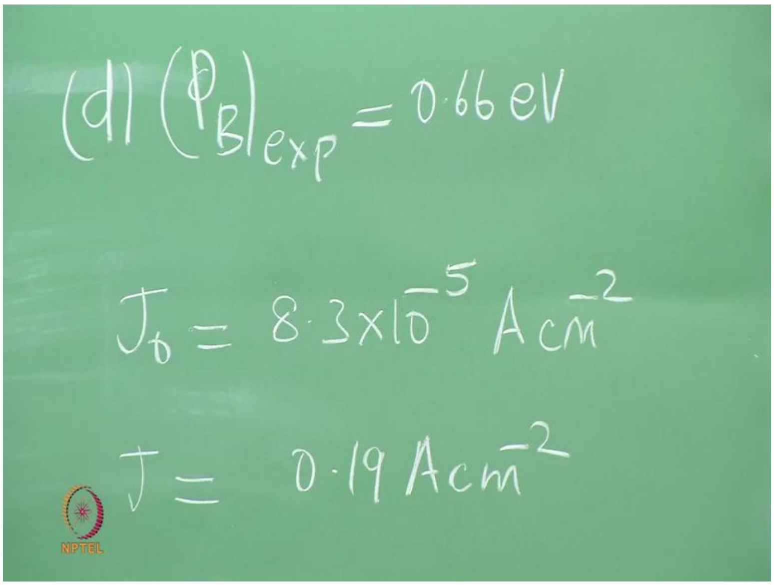

In part-d, question says that the experimental Schottky barrier is actually higher, so φ_B experimental is 0.66 eV. So, it wants us to do a recalculation. So, This experimental value takes into account, the fact that the interface is never perfect that you always have some sort of defects at the interface. So, If you use this, we can use the same calculations that we just did except that now we have to use the newer value of φ_B. So, in this particular case, J_o comes out to be 8.3 x 10^{-5} A cm^{-2} and current J is 0.19 A cm^{-2}. So, The actual current is slightly lower than what we would accept if we use the theoretical values, but the important fact is that it is still 4 orders of magnitude higher than J_o, so that a Schottky diode, a Schottky junction still functions as a rectifier. So, let us now go to the next problem.

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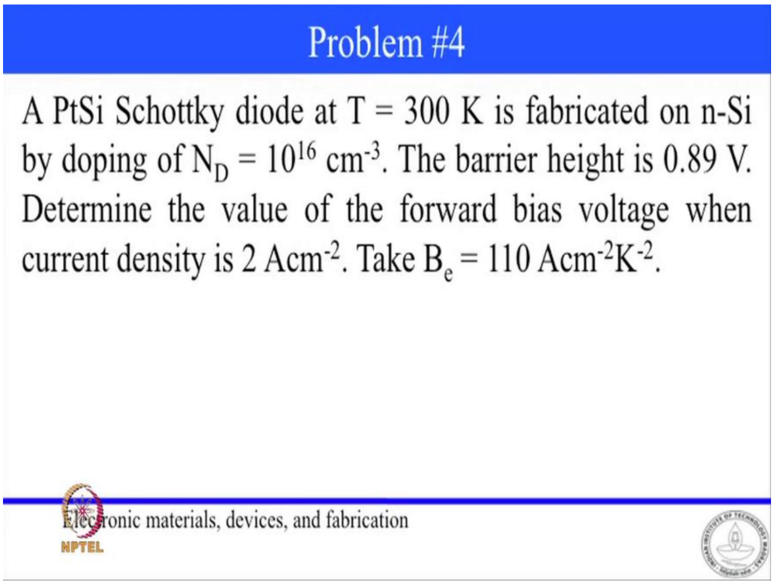

So problem 4: we have a Platinum Silicide Schottky diode, is fabricated on n-Silicon. So you have platinum silicide on silicon. So, how this is usually obtained? Is by first depositing platinum metal, usually it is done by some vapor deposition process like thermally evaporation or sputtering or e beam evaporation. Then, the interface is annealed, so that we have inter diffusion between platinum and silicon which again react to form the silicide. So, depending upon the composition you can get a single composition Pt Si or if you get multiply compositions, again depends upon the thickness, the platinum layer and the amount of inter mixing. So, These silicide layers are usually formed by depositing the metals and then doing some sort of a post annealing treatment.

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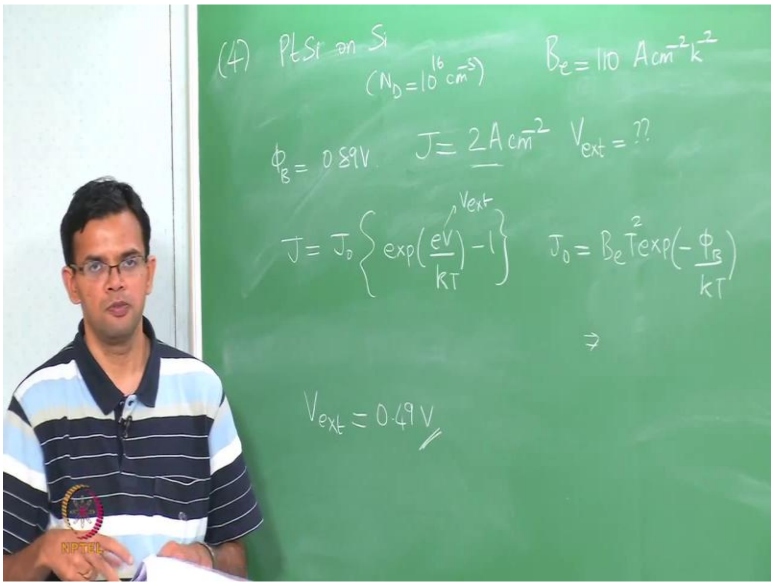

So, in this particular case, it is n-type silicon. So, N_D is 10^{16} cm^{-3} the barrier height. In this particular problem is given φ_B is 0.89 volts. So, One of the advantages of doing a post annealing is at that usually eliminates some of the defects, so that your barrier is essentially very close to your theoretical barrier. So, once again we want to calculate, So, the forward current is known, so J is given to be 2 A cm^{-2} and we want to calculate the value of the voltage. So, V external is want we want to calculate. We can go back and use the same equation, J is equals to $J_o \left[exp\left(\frac{eV}{kT}\right) - 1\right]$. $J_o$is nothing but $J_o = B_e T^2 \left[exp\left(\frac{-\phi_B}{kT}\right)\right]$. So, the value of B_e, for this problem we can still take the same value 110 A cm^{-2} K^{-1}. We can use this and calculate J_o. So, J_o is just got by substituting $B_e T^2 \left[exp\left(\frac{-\phi_B}{kT}\right)\right]$. Once we get the value of J_o, you can put the value of J_o here. We need to know the value of J. So, J is given to be 2 A cm^{-2}, the only thing that we do not know is V external. So, Once we calculate J_o we can plug it here and get V external. So, I will just write the answer V external for this particular problem is 0.49 volts, but the calculation is very similar to what we did the previous problem. So, let us now go to problem 5.

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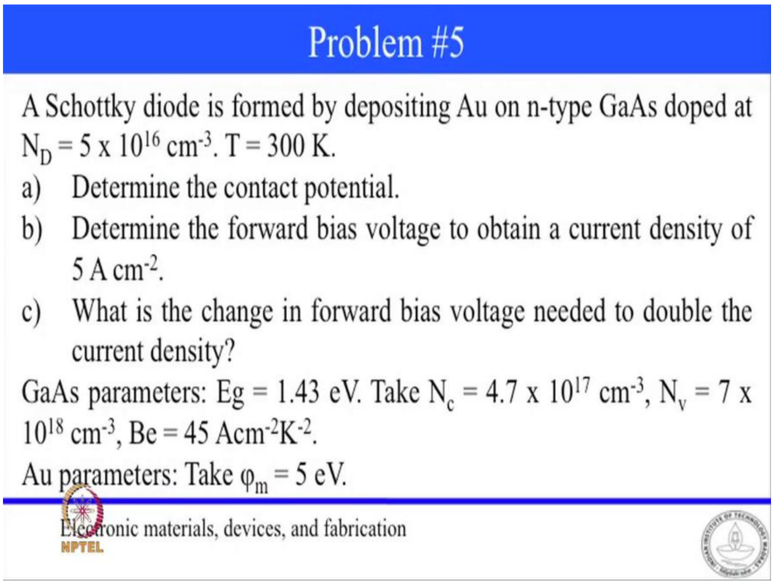

Problem 5: we have a Schottky diode formed by depositing gold, but now the material is n-type Gallium Arsenide.

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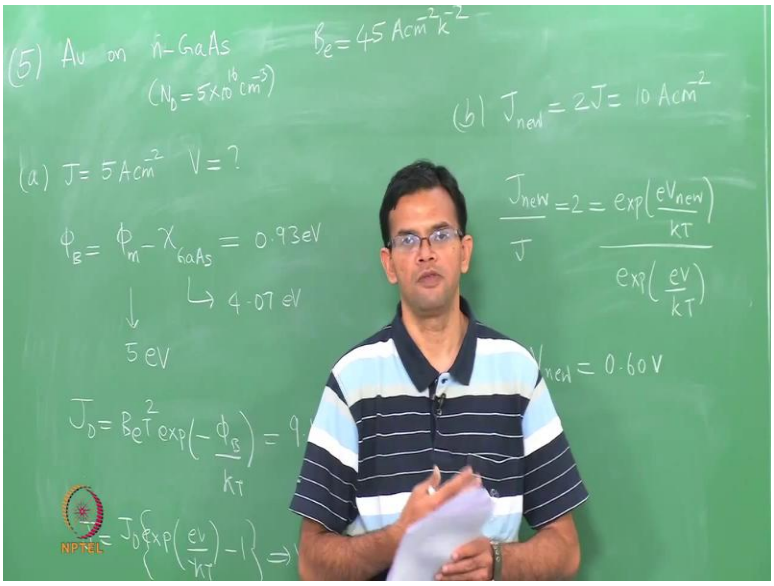

So, We have n gallium arsenide with N_D is 5×10^{16} cm^{-3}. So, once again in part-a, we need to calculate the forward bias voltage for a current density. So, J is 5 A cm^{-2} and we need to calculate the voltage for that. This is again similar to the previous problem.

Now, the material is gallium arsenide. So, the first thing we need to do is to calculate the barrier potential, we are going to assume that it is a theoretical barrier. So, we need to know φ_B, which is nothing but phi m minus the electron affinity for gallium arsenide. In this particular case, E_g of gallium arsenide is given, but more importantly we only need the electron affinity, this as a value of 4.07 eV. So, We can still use the other values to calculate the contact potential, but as far as part-a is concerned the only thing we need to know is the electron affinity. So, φ_m is given to be 5 electron volts, So, this is the work function of gold. The electron affinity of gallium arsenide is known so that the theoretical barrier potential is nothing but 0.93 electron volts.

So, Once we get that we can calculate J_o. Again, for the gold and gallium arsenide interface we have the values for B_e. $B_e = 45$ A cm^{-2} K^{-2}. So, B_e is not only a material property it also depends upon what facet of the material you have, whether you have a 100 plain or 110 or 111 that will also affect the value of B_e. So, J_o is a number we can calculate, all the numbers are known so this is nothing but 9.1×10^{-10} A cm^{-2}. J_o is known, J is known $\left(\frac{eV}{kT}\right) - 1$. So, again J is known, J_o is known, the only think that is unknown is V, from which we get V to be 0.58 volts.

In part-b, we need to calculate the change in the forward bias voltage to double the current density. So J new, which is your new current density, is 2 times of the old one, so this should be 10 A cm^{-2}. You can either take the ratio of the old and new J or it could use the same equation $J_o \left(\frac{eV}{kT}\right) - 1$. You can calculate, so if you take the ratio J_{new} - J which is 2 is equal to $\left(\frac{eV_{new}}{kT}\right) - 1$ by $\left(\frac{eV}{kT}\right) - 1$, so V is known we just calculated that in part-a the only thing we need to do is to calculate is V_{new}. And, V_{new} is 0.60 volts. So, In the case of a Schottky junction which is essentially a rectifier. We have seen how to calculate the Schottky barrier voltage, the built-in potential and also the current during both forward and reversed biased. An Ohmic contact is much simpler and Ohmic contact is essentially a resistor and a resistivity is usually given by the resistivity of the semiconductor material.